TERRAIN ANALYSIS AND SITE EVALUATION: INTEGRATING A GEOSPATIAL APPROACH FOR SUBTROPICAL FOREST MANAGEMENT PLANNING

(地形解析及び立地評価：亜熱帯森林管理計画への地理空間情報の統合化)

Azita Binti Ahmad Zawawi

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Thesis

As partial fulfilment of the requirements for the degree of
Doctor of Philosophy in Regional Resource Environmental Engineering
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Kagoshima University, Japan

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By
Azita Binti Ahmad Zawawi

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Guided and supervised by:

芝 正己
....
Professor Dr. Shiba Masami (芝正己)
University of the Ryukyus
Okinawa, Japan

To my beloved parents for
being the pillows, cheerleading squad and for always
encouraged me to go on every adventure,
especially this one

Abstract

Terrain Analysis and Site Evaluation: Integrating a Geospatial Approach for Subtropical Forest Management Planning

This study demonstrates methods to map terrain variability and analyze the relationship between terrain characteristics and site suitability for sustainable forest management planning. An assessment was conducted in the Yambaru Forest Area (YFA), located in the northernmost part of Okinawa Main Island, Japan. Preservation and conservation of the natural environment in this area is a major issue, which requires more efforts for effective forest management. Presently, efforts are being made to designate the YFA as a national park due to its listing as a Word Natural Heritage. Spatial evaluations of the area were completed using various geospatial tools within GIS according to three objectives.

The first objective was to characterize landform features of YFA using an automated classification technique. Landform classification was performed using Digital Terrain Model (DTM) based on a Topographic Position Index (TPI). The process resulted in identifying ten landform classes that differentiate the slope positions of the area. Selected terrain variables were integrated into vegetation data for site evaluation. The Normalized Difference Vegetation Index (NDVI) values for the study site range between -1 and 0.77, suggesting a strong relationship between forest cover, tree height and slope position. In this chapter, the interaction between landform type, terrain characteristic and forest functions were critically discussed.

The second objective presented a method for erosion hazard site identification using Light Detection and Ranging (LiDAR) data. SAGA GIS software was effectively used to simulate secondary terrain attributes related to erosion development namely LS factor, SP index, and TW index. Vegetation cover analysis was completed by using the extraction of the Digital Canopy Height Model (DCHM) from the LiDAR data. All parameters were integrated, and a slope failure hazard map was produced. For verification, the simulated hazard map was then compared with the ground truth data of slope failure locations. Results indicated that 84.6% of a slope failure recorded from field verifications fall within the severe identified zones in the simulated map, associated with forest road construction.

The third objective aimed to examine the effects of terrain characteristics on stand structure and diversity through a combination of ground-based plot studies and computer-based spatial analyses. Vegetation indices consist of tree height, DBH, stand density, stand basal area, species' richness and a Shannon-Wiener diversity index were calculated from field measurements and correlated into terrain variables derived from the LiDAR data. Results suggested that species' richness between plots varied from 15 to 30 species. A Shannon-Wiener diversity index, tree height and DBH were significantly correlated with terrain factors. An assessment of site characteristics and its relationship with forest structure provides essential information for forest inventory and monitoring.

Each chapter in this thesis discussed the application of terrain analysis for site evaluation in a subtropical forest setting with heterogeneous terrain conditions. It provides a significant contribution to the understanding of interactions between terrain characteristics, hazard prediction and forest site productivity in YFA. Information and analytical methods discussed in this study will be beneficial for forest management planning, especially in the complex subtropical forest of Okinawa Island.

要約

地形解析及び立地評価：亜熱帯森林管理計画への地理空間情報の統合化

本研究は地形の変動特性を地図化する手法および持続可能な森林管理計画策定のための地形特性と立地の関係を解析する手法を提示している。沖縄本島北部に位置するやんばる森林(YFA)を評価対象地とした。この地域の自然環境保全の問題は重要となっており、より効果的な森林管理の実践が求められている。現在、世界自然遺産登録の担保処置として、やんばる森林地域の国立公園化への努力がなされている。当該地域の空間評価を目的とする 3 研究課題について、GIS の地理空間情報処理手法を援用した。

まず、やんばる森林地域の地形特性について自動分類法を導入して検討した。地形分類には、地形位置指標 TPI に基づく数値地形モデル DTM を用いた。斜面位置の違いにより対象地域は 10 タイプの地形に区分された。立地評価を目的に、選択した地形変化量と植生データを統合化した。解析対象地の正規化植生指標 NDVI 値は、被覆森林、樹高及び斜面位置間の強い関係を示しつつ、-1~0.77 の範囲を与えた。本章では、地形タイプ、地形特性及び森林機能の相互関係を主眼に議論した。

次に、航空搭載型レーダ(LiDAR)データを用いて崩壊危険個所の判定法について検討した。崩壊過程に関係した二次的地形属性である LS factor、SP index 及び TW index を用いて、SAGA GIS による崩壊地形のシミュレーション分析を行った。また、LiDAR データから推定した数値樹冠高モデル(DCHM)によ

り植生被覆状態の評価を試みた。これらの地形及び植生に関するパラメータを総合化して崩壊危険箇所地図を作成した。この地図の精度検証は、崩壊発生個所に関する現地調査結果との比較から行った。その結果、現地で確認された林道開設に関係する崩壊箇所の 84.6%が地図上の高危険判定区域で起きていることが確認された。

3 番目の課題として、地上設定プロット及びコンピュータによる空間解析から、地形と林分構造及びその多様性について検討した。植生指標として樹高、胸高直径、林分密度、胸高断面積合計、種多様性、シャノン・ウィーナー指数を野外測定から算定し、LiDAR データから導出された地形変数との関係を検討した。プロット間の種多様性は 15～30 の種数の違いとして現れた。シャノン・ウィーナー多様性指数、樹高及び胸高直径は地形因子と有意な関係があった。地位特性の評価及び林分構造との関係は、森林調査やモニタリングにとって不可欠な情報を与える。

本論文の各章で、地形の違いによる亜熱帯森林の環境状況を地形解析を応用して議論した。これらの結果が、やんばる森林地域の地形特性、崩壊危険個所予測及び地位評価に関する相互関係を理解する上で有効であることがわかった。それゆえ、本研究での情報や解析方法は、沖縄の複雑な亜熱帯森林の管理計画策定に有効となると思われる。

Layout and Outline of Thesis

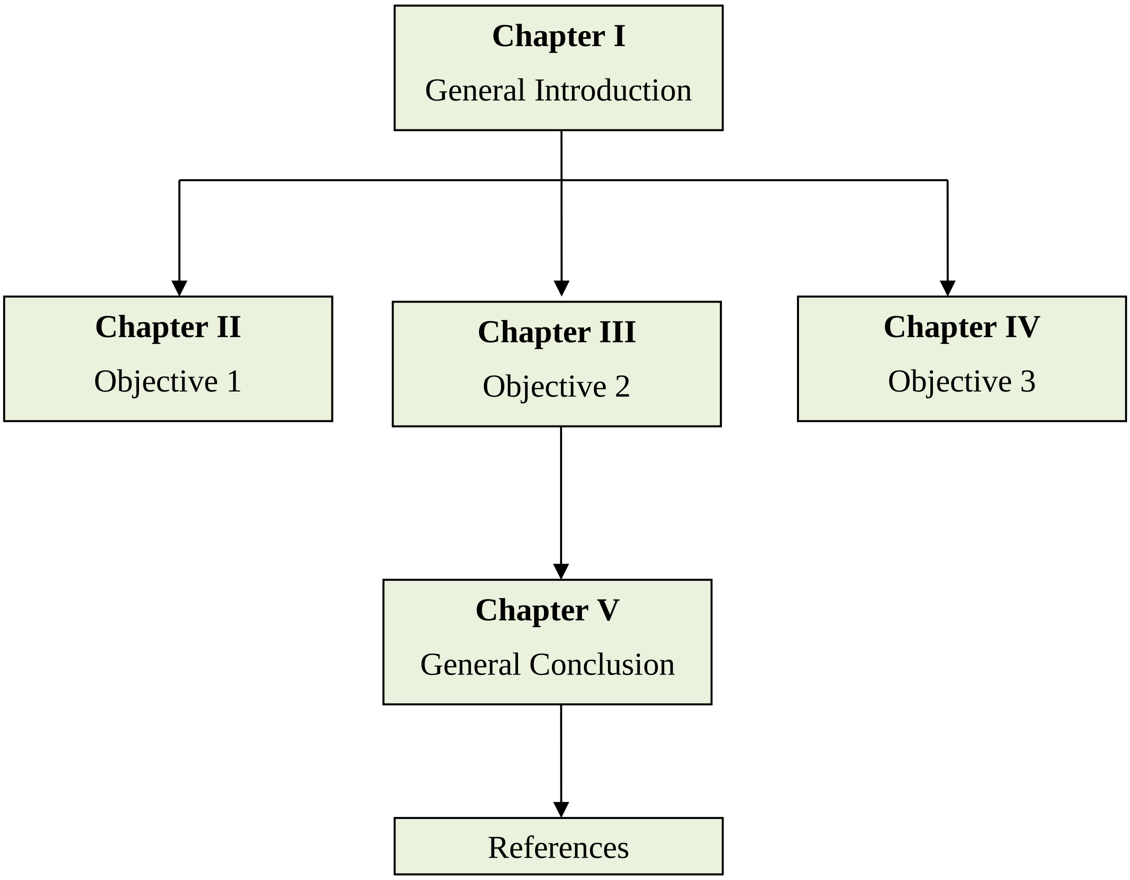

Figure-A.

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List of Abbreviations

DBH	Diameter at Breast Height
DCHM	Digital Canopy Height Model
DEM	Digital Elevation Model
DSM	Digital Surface Model
DTM	Digital Terrain Model
GIS	Geospatial Information System
LiDAR	Light Detection and Ranging
LS Factor	Slope-Length Factor
NDVI	Normalized Difference Vegetation Index
r-EPI	Erosion Potential Related Indices
SABO	Japan Society of Erosion Control Engineering
SAGA	System for Automated Geoscientific Analysis
SP Index	Stream Power Index
STFRJ	Society for The Forest Road of Japan
TPI	Topographic Position Index
TR Index	Terrain Ruggedness Index
TW Index	Topographic Wetness Index
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation
YFA	Yambaru Forest Area
3D View	Three Dimensional Visualization

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`Good company in a journey makes the way seem shorter`

Izaak Walton

Chapter I

General Introduction

1.1 Key concepts: Digital terrain analysis, GIS and site evaluation

Landform and terrain characteristics play a major role in forest ecosystem use and management. An increasing demand for forest products, tourism development as well as the importance of nature conservation has become increasingly complex. Land use development and conservation in conflict zones involves a range of challenges from understanding environmental characteristics to policy management, thus calling for new approaches for forest monitoring and project implementation. The process of characterizing terrain is known as terrain analysis, and consists of the quantitative analysis of topographic surfaces that are crucial for forest management and planning (Basso 2005).

Digital Terrain Model (DTM) is defined as a representation of land surface points derived from photogrammetric data, satellite image, laser scanning data, or manual delineation by ground survey (Forkuo 2008, Weibel & Heller 1990). In several other studies, a similar definition was addressed as DEM or Digital Elevation Model (Gallant & Wilson 2000, Hengl et al. 2003, Miller & Laflamme 1958). In this study, the term DTM was consistently applied to describe gridded elevation points. DTM plays a significant role in hydrologic modelling, soil erosion prediction, drainage morphology, vegetation classification and ecology. The application of DTM was introduced as early as 1950s (Miller & Laflamme 1958) and has become a major constituent of geographical information processing throughout the years.

The Environmental Systems Research Institute (1994) described GIS as a system to organise a collection of computer hardware, software, geographical data, and is specifically designed to capture, store, update, manipulate, analyse, and display all forms of georeferenced information (Köhl et al. 2006) (**Figure 1-1**). GIS technology has evolved drastically over the last few decades. The application of spatial data such as satellite-based remote sensing in forest monitoring, land mapping, and management planning was recognized earlier by several researchers (Trotter et al. 1997, Mollicone et al. 2003) to explore conflicts, examine impacts and assist decision-making. An assessment and systematic evaluation of natural resources can be better managed by proper and efficient tools especially in large regions. A combination of multiple applications integrated within GIS provides outputs that will help the decision-making process work more efficiently and save time. Within a GIS environment, DTM is very useful and is valuable as primary data for the extraction of terrain related information (Weibel & Heller 1991, Moore et al. 1993). Therefore, geospatial technology approaches serve a major role in examining the suitability of forestry activity related locations, auditing environmental conditions, identifying conflict zones and modelling relationships (Bahaire & White 1999). The advance tools within GIS also provide multiple techniques and technologies for better analysis and presentation of natural resources to achieve sustainable management.

Site evaluation is defined as a process of assessing the potential production and constrains of various land uses (Beek 1978, Trejo 2014). This approach is based on matching qualities of different land units in a specific area (FAO 1993). The result of site evaluations should be useful for rational land use and the supporting data is important and necessary for developing a country that is usually under severe environmental and demographic constrains (Bocco et al. 2001).

Terrain analysis has contributed to forest research and development in various field and study areas. Other than for a simple characterization using primary terrain attributes (slope, aspect, curvature), terrain analysis is very useful for improving environmental information especially in soil survey and land evaluation (McKenzie et al. 2000). Additionally, digital terrain analyses using DEM and/or DTM provide a three-dimensional view (3D view) of the ecosystem landscape. Its integration with other spatial data combined with more advance analyses could lead to other studies such as microclimate studies, hazard prediction and many more.

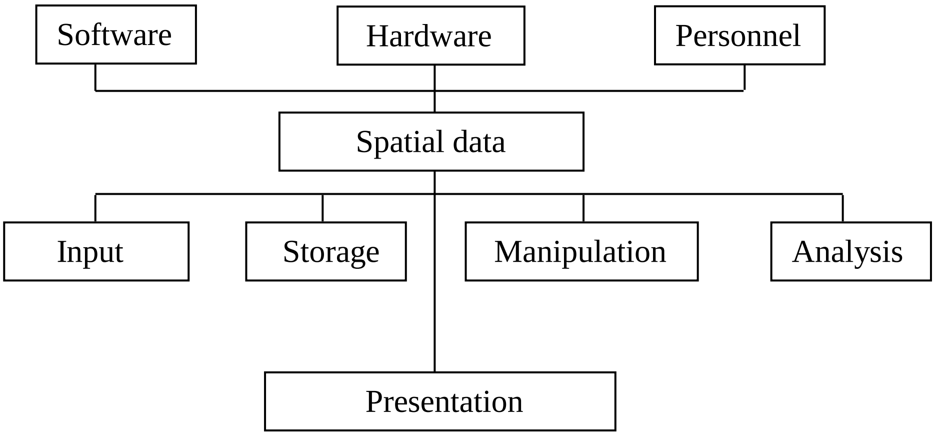


Figure 1-1. Conceptual framework of GIS adapted from Köhl et al. (2006)

1.2 Background of study

Okinawa which is the south-westernmost part of Japan comprised of 2265km^2 is the only Japanese prefecture within a subtropical climatic zone (**Figure 1-2**). Its chain of islands spans a distance of 1000km from north to south and 400km from east to west (Kakazu 2000). Preservation and conservation of the natural environment in the northern area is a major issue which requires more cooperation and effort to sustain management of forest resources. The study site is the Yambaru Forest Area (YFA), located in the northernmost part of Okinawa Main Island (**Figure 1-3**). With a total area of 340km^2, this mountainous forest area covers the coastal ranges of northern

Okinawa and has a highly diversified georelief as well as high species richness (Ito 2003). The area is rugged, mountainous, and wooded, elevation ranges from sea level to 503m, but unique terrain characteristics differentiate the eastern and western sides of the region (**Appendix-1 to Appendix-6**). The bedrock is composed mainly of Tertiary sandstone, and a red yellow forest soil (Kojima 1980). The western area, which is geomorphologically hilly receives a higher population consisting of various land uses while the eastern area is smoother with lower degrees of slope. This small forested area plays a major role in Okinawa, not only for ecological and biological purposes, but also for its aesthetic and spiritual values.

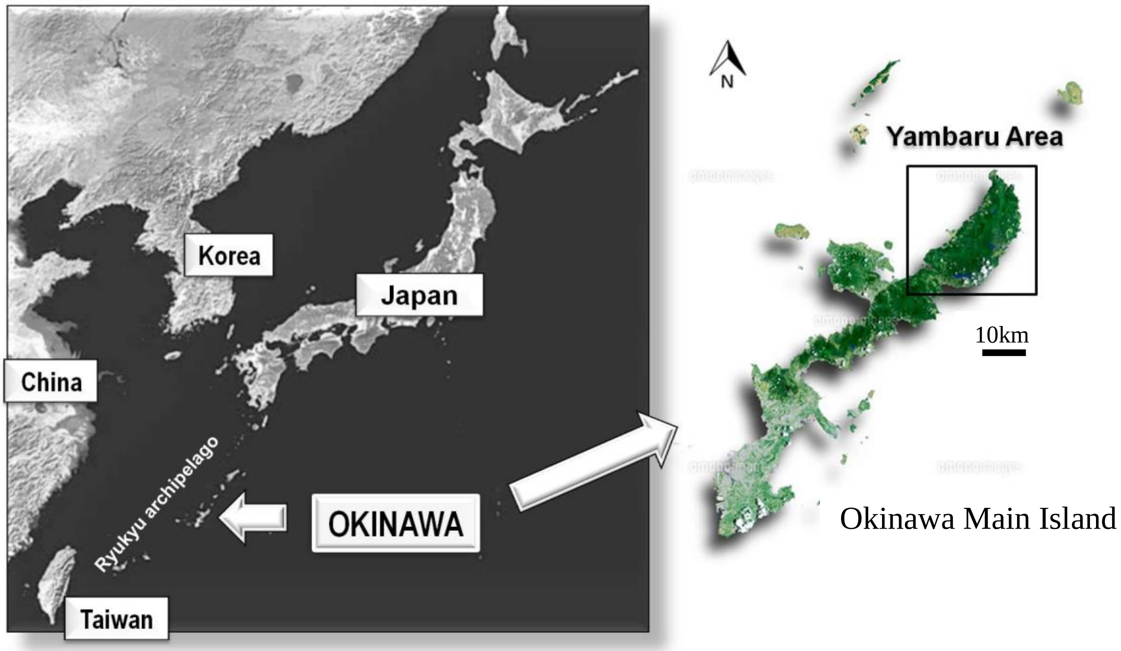


Figure 1-2. Location of Okinawa Island and Yambaru Area

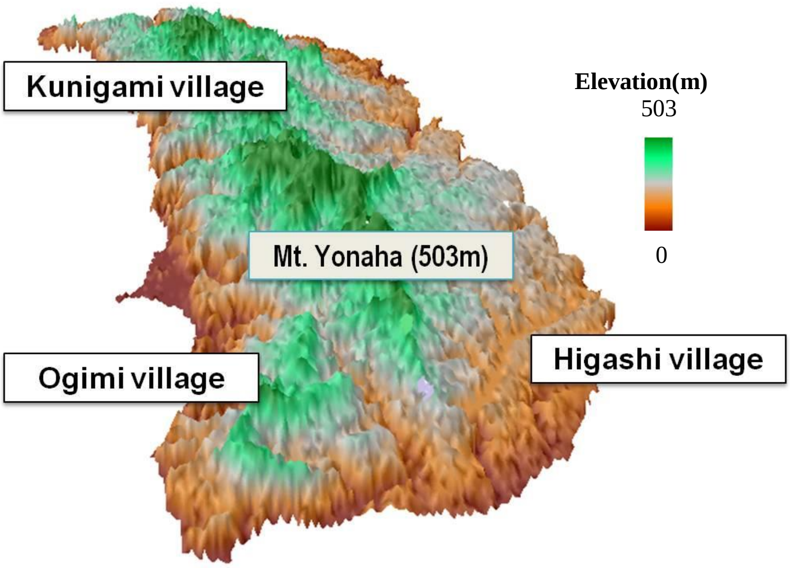


Figure 1-3. Northward expand overview of Yambaru Area

1.3 Problem statement and justification of the study

1.3.1 The case of Yambaru

The Forest of Okinawa Island has faced a number of environmental concerns influenced by climatic factors, economic concerns, political issues as well as socio-ecological factors. The forest area is very small, yet has to fullfill various needs from the population. Presently there are efforts to designate the YFA as a national park due to its listing as a Word Natural Heritage. However, YFA is facing a conflict between its developmental ambitions and conservation plans (Takeuchi et al. 1981, Omija 2004). Exposure to strong winds from typhoons, road construction in a steep watershed area and their combination with other environmental factors that include topography, soil and geologic type have become a threat that leads to severe forest damage. There are several studies that indicate the influence of topographic characteristics to forest conditions in Okinawa Island. As an example, slope failure related to forest road construction and the influence of typhoons have been continuous problems for the island (Kabeya et al. 2014, Roy 2006, Sakai et al. 2005). The situation influences community safety as well as a degradation of aesthetic values for the impacted areas. A successful forest management plan could be achieved by considering various factors including topographical factors, climatic influence, community needs, socio-ecology, as well as hazard assessments. The difficulty in monitoring the forested site due to limited ground resources and low accessibility to the forest area have served as limitations for detailed site assessment and evaluation. There is a substantial requirement to introduce feasible methods of forest and terrain characterization using limited resources and data operation skills that would be beneficial for forest managers and scientists. The application of digital terrain modelling and GIS technology has been proven decades ago as an effective approach for overcoming these limitations. A detailed analysis of terrain characteristics of the area is very important for mapping land variability and predicting topographical constraints for further land use evaluation and forest planning.

1.4 Main objectives and research approaches

Concerning the aforementioned issues, the main objectives of the study are:

1. To quantify landform characteristics for site evaluation and forest management planning in the Yambaru Forest Area with the integration of a traditional concept.
2. To introduce a method to identify and map slope failure hazardous sites using digital terrain simulations in the steep forest of Yambaru.
3. To assess the influence of terrain characteristics on stand structures and tree diversity in Yambaru Forest Area.

In this study, various aspects of terrain characteristics were analysed, which correspond to hazard assessment and site evaluation. Spatial evaluations and calculations on terrain characteristics and values were conducted using multiple applications of GIS. Considerations were completed according to engineering and environmental constraints for a better definition of forest use. Results provide a set of information for forestry officials, decision makers and land practitioners for sustainable forest management of the area.

1.5 Significance of the study

A terrain analysis approach presented in this study offers alternative techniques for the assessment of micro topography and the evaluation of landform units using minimal data resources. Integrating this with user-friendly GIS tools opens up the opportunity for foresters, researchers and forest practitioners to characterize the forest structure from the perspective of terrain features. The results suggest that an effective assessment of terrain features serve as an important factor for hazard prediction as well as for controlling forest structure and site suitability.

In YFA, forest and land resource information may be obtained using traditional and manual procedures such as ground surveys and geomorphological mapping. However, with regards to its rugged and mountainous terrain, the integration of DTM and other forest cover information may produce a set of databases that offers a significant reduction in cost, working times, and labour usage. Additionally, predictive terrain modelling within a GIS environment allows for multiple data formats when it comes to achieve the effective restoration and management of the data and to produce interactive digital maps.

1.6 Framework of research methodology

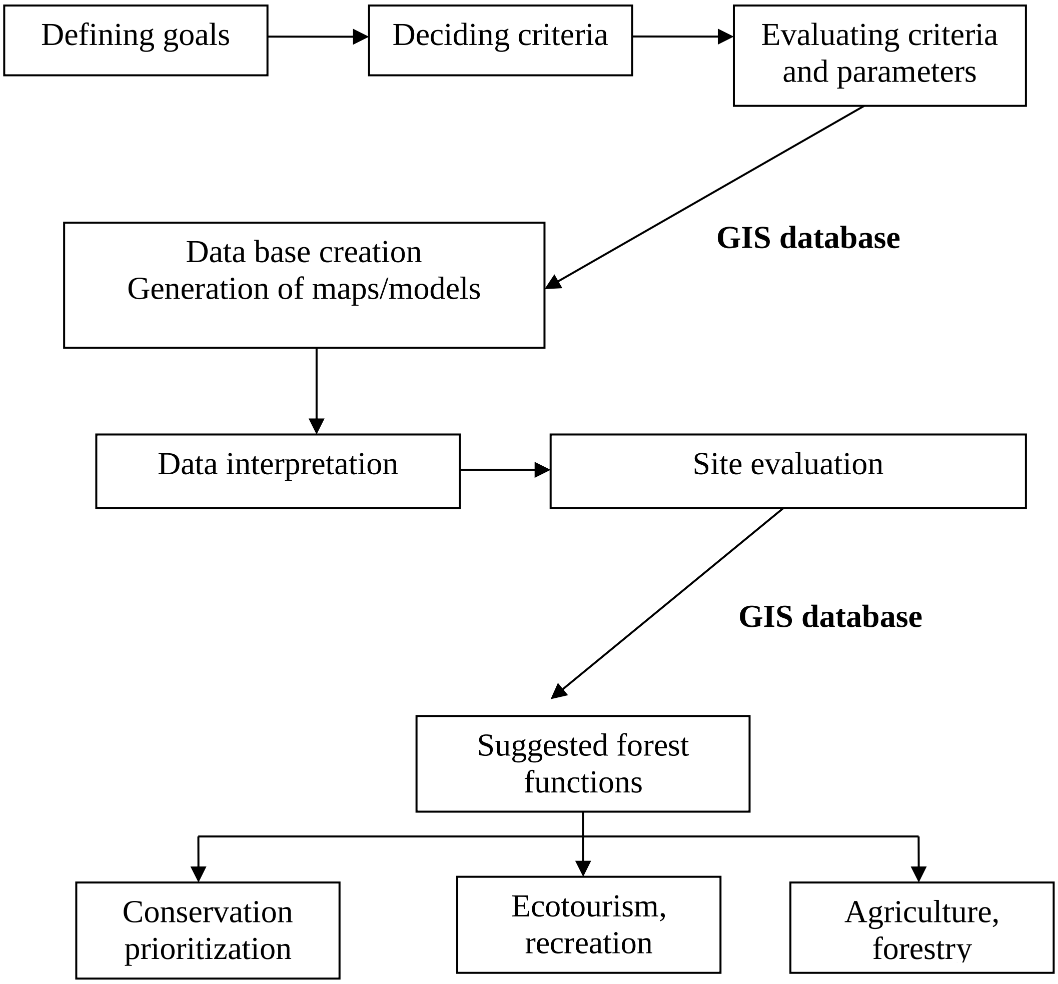


Figure 1-4. Framework of research methodology

Chapter II

Landform Classification for Site Evaluation and Forest Planning: The Integration between Scientific Approach and Traditional Concept

2.1 Introduction

Topography heterogeneity on a local scale plays an important role in forest management, productivity, and diversity (Kubota et al. 2004). Terrain and landform analysis along with additional information, such as surface geology and soil data, will help in understanding the topography of the region and determining the most appropriate sites for various land uses. Better understanding of the process is a key point to conduct forest planning and to achieve successful forest management. Many studies were carried out to map the variability of natural resources and landform classification to assess land capabilities. Historically, Dikau (1989) had previously introduced an approach to identify plateaux, convex scarps, valleys, and crests; Gardner et al. (1990) developed methodologies to extract terrain features while Cheng et al. (2005), Azanon et al. (2001) and Bailey (1987) proposed an approach to delineate land into ecosystem units using topographical parameters and cluster analysis. Another significant study was done by Dragut and Blaschke (2006), who applied object-based image analysis in landform classification. Topographical variables and DTM are easily observable features which have a high accuracy, and are relatively stable in the landscape. Therefore, they are very effective for land classification especially site evaluation and forest planning (Fabian 2004, Yanni 1996). Many of these classifications, however, require detail steps and extraction of various primary terrain attributes. Comparatively speaking, SAGA GIS (System for Automated Geoscientific Analysis) software, which was developed by a team of geospatialists at the Department of Physical Geography, University of Göttingen, Germany, facilitates faster geomorphometrical calculations and terrain computations. This particular software has been designed for easy and effective implementation of spatial algorithms. In this study, the application of SAGA GIS was tested on a small watershed in YFA. The dense subtropical forest starts as near as 10m from the coastline and the highest elevation is only 503m. Receiving monsoonal typhoons and strong winds directly from the coast side places the threatened area under complex and severe forest conditions. Detailed analysis on terrain characteristics of the surrounding area is very important to map the land variability and predict topographical constraints for further forest evaluation. However, endangered and poisonous species that inhabit the island have limited accessibility for forest managers to monitor the area directly, which is one of the pertinent challenges in managing the mountainous forest. To overcome this issue, terrain analysis and modelling work best to give the managers insight into forest resources and condition.

2.1.1 Concept of terrain analysis and sustainable forest management introduced by Sai-on in Sanrin Shinpi - The secret of forestry

Back in 1751 in the political history of Okinawa Island (formerly known as Ryukyu Kingdom), Sai On, who is a member of the state council, introduced a ‘Theory of Forest Terrain,’ which emphasized that terrain characteristics should be the primary factor in choosing a location to use especially for forestry and agriculture purposes. Sai On had previously conducted a thorough study of forest growth and methods of forest land use planning, which were documented in several phases (Mitsugu 2000). The concept introduced was influenced by the natural environment of the island and the requirement of managing the forest area against seasonal wind and/or strong typhoons. The book produced, Sanrin Shinpi, emphasized that there are four key points to be considered in forest management and planning: (1) terrain characteristics, (2) a geomorphic concept of embraced protection, (3) the management of timber, and (4) the appearance of a forest (Purves et al. 2009). In the document, land characteristics were divided into few levels and described comparatively regarding the functions of each level with the influence of 'feng-shui' (**Figure 2-1**). Holding on to the earlier concept of terrain analysis documented in Sanrin Shinpi, spatial evaluations and calculations on the landform elements and values were done using multiple applications of GIS.

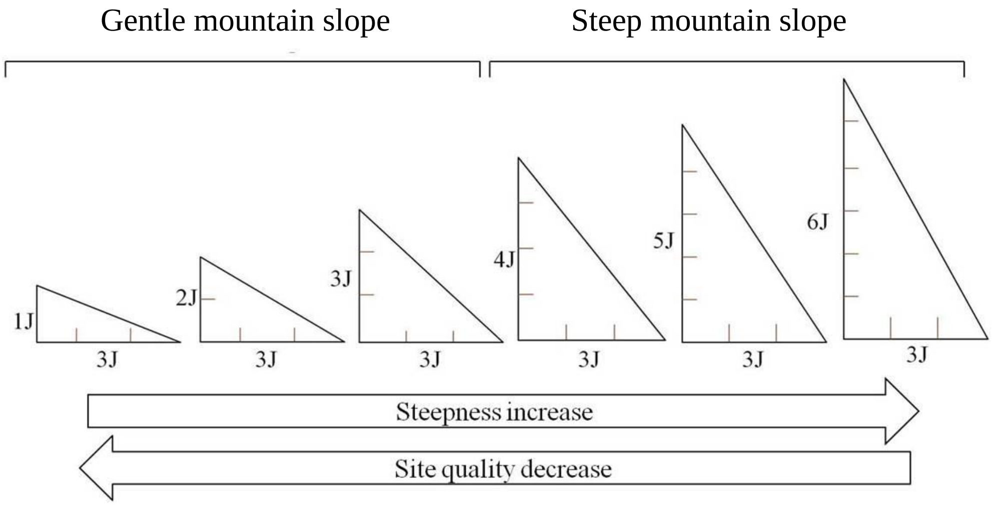


Figure 2-1. Traditional terrain classification illustrated by Sai On in Sanrin Shinpi: The Theory of Forest Terrain

Remark: Traditional measurement unit (J) = Jo (丈), where 1J = 3.03m

2.2 Materials and methods

2.2.1 Study area

Figure 2-2 shows the forest site selected for this study. This region covers 10.75km^2 of YFA and has a highly diversified georelief.

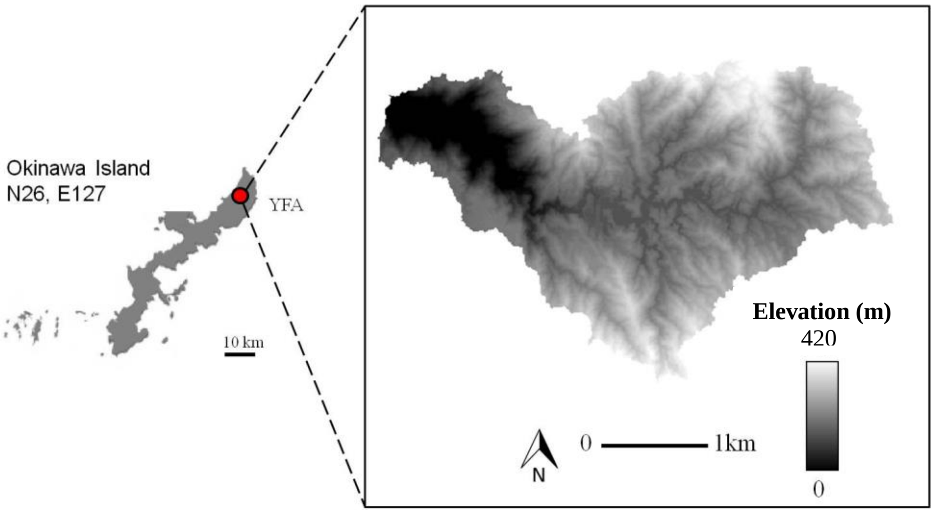


Figure 2-2. Location of Okinawa Island and the study site illustrated by elevation map

2.2.2 Data processing and analysis

Throughout the assessment, we comprehensively used; (i) interpretation of terrain and landform maps derived from the DTM, (ii) interpretation of the IKONOS satellite image for land cover assessment, and (iii) interpretation of remote sensing data of vegetation height (resolution at 1m). All data layers were then incorporated and zonal statistic analysis was done to describe the quantitative relationship between the variables. Site evaluation was done with respect to comprehensive literature reviews from recent studies as well as traditional concepts by Sai On.

The study used DTM of YFA with a spatial scale of 10m x 10m supported by the Geospatial Information Authority of Japan. According to Hutchinson and Gallant (2000), DEM/DTM with a resolution of 5 to 50m was defined as fine scale, which was suitable for various analyses including for soil, hydrological modelling, and terrain analysis. Terrain analysis and computation was divided into two main sections; i) the computation of secondary terrain attributes that characterized the landform and ii) automated landform classification for the whole watershed area. SAGA GIS software was effectively used in this process.

2.2.3 The computation of secondary terrain attributes

The first step was conducted by an automated derivation of primary terrain attributes which are slope, aspect and catchment area. These parameters which had a significant influence on hydrological processes and landform development were simulated using numerical expressions to produce secondary terrain attributes namely topographic wetness index (TW index) and terrain ruggedness index (TR index). Each of these attributes was selected as their algorithms differentiate grid cells that are related to soil-forming process. The terrain indices were expressed as below:

$$\text{TW index} = \text{In}\ (A_s\ /\ \tan \beta)$$

where A_s = Catchment area (m^2/m) , β = slope in degree

The formula was taken after Wilson and Gallant (2000). TW index was constructed by considering two shapes of slope; concave and convex. Concave slope in low gradient areas will gather water and have low TW index while convex slope in steep area will shed water and contribute to higher TW index value.

$$\text{TR index} = (\text{TNC} \times \text{TNF})\ /\ (\text{TNC} + \text{TNF})$$

where TNC = the total number of contour intercepts along the transect

TNF = total number of fluctuations

TR index calculation was done following a formula introduced by Nellemann and Thomsen (1994). This formula incorporated the effects of slope and terrain undulations, where area with many contour intercepts will produce high value and steep but smoother terrain will have low values (Nellemann & Gareth 1995).

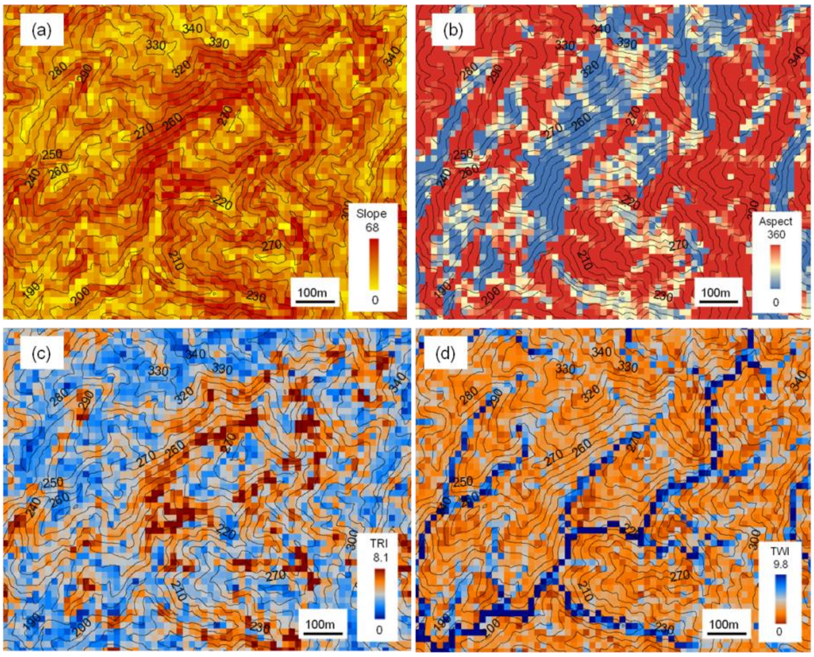


Figure 2-3. Major terrain variables characterized in the landform classes (a) Slope (b) Aspect (c) TR index and (d) TW index. Contour distance was set at 10m.

2.2.4 Landform classification techniques

The analysis was performed trough the simulation of DTM to obtain topographic position index (TPI) in morphometry module within SAGA GIS. The process calculate the difference between elevation at a specific cell and the average elevation in its neighbouring cells (Tagil & Jenness 2008); describing higher and lower areas which classify the landscape into different morphological classes (Jenness 2005). Unsupervised classification process was done to the DTM following Jennes (2006) and Weiss (2011). The simulation requires setting the radius of the neighbouring cells and its geometric shape based on two different scales or two sizes of radius (Barka et al. 2011). In this study, a radius between 50 and 1000m was applied to determine the slope positions. Gaussian and exponential weighting with bandwidth value of 75 was used. The process generated 10 classes of landform features. Zonal statistic and correlation analysis were done to evaluate the relationship between each landform type and selected terrain attributes.

2.2.5 Forest covers classification using NDVI analysis

For vegetation evaluation, two types of maps, satellite image and tree height, were used, provided by the Department of Agriculture, Forestry, and Fisheries, Okinawa. Normalized Difference Vegetation Index (NDVI) analysis was done on a multispectral image from an IKONOS-2 satellite acquired on 6 February 2007, datum WGS84, with high resolution imagery at 4m and 1 percent cloud cover. The image was octhorectified by the JSI (Japan Space Imaging). NDVI was calculated using the formula, NDVI = (NIR – Red) / (NIR + Red), where the values varied between -1 to +1. Low NDVI value reflects sparse or unhealthy vegetation, while higher value represents greener plants (**Table 2-1**). Tree height value was calculated by subtractions of the DTM from the DSM derived from remotely sensed LiDAR data at a resolution of 1m. The data were collected in April 2011 using ALTM 3100 CASI-3, with flight altitude at 1100m. The scan frequency was 39Hz and scan angle was ±20°. The data were collected with a small footprint of 0.2mrad and laser wavelength of 1064nm. The tree height map obtained was reclassified into seven classes to differentiate its effect on topography. Vegetation cover is an important factor as it has a strong relation to root strength that represents site quality and land use suitability.

2.3 Results and discussions

2.3.1 Landform characteristics and descriptions

Major terrain variables characterized in the landform classes are presented in **Figure 2-3.** The image shows the relationship between each variable and terrain steepness where slope, TR index and TW index changes as the terrain become steeper and complex. All these terrain factors are very important to understand the topographical condition of the study site. The study area was classified into ten different landform types: high ridges, midslope ridges, upland drainage, upper slopes, open slopes, plains, valleys, local ridge, midslope drainage, and streams, respectively (**Figure 2-4** and **Figure 2-5)**. Different colours and patterns on the map denote significant landform features and describe the geographic location of major landforms. Quantitative data are summarized in **Table 2-1**. The study site is formed from flat to rugged terrains and gently sloping to hilly areas. Lower elevations concentrated near streams and valleys, having slope categories ranging from 0 to 68°, and dense forest area starts from a distance of 5 to 10m above sea level. High ridges covered 4.82% of the examined area with a mean elevation of 292.15±64.33m. Slope level in high ridges was considered moderate to steep with a mean value of 21.77±9.74° but low TW index of 3.20±0.81. Midslope and upland drainage covered 10.48 and 0.64% of the total area with slope values of 20.75±8.74° and 29.22±10.88°, respectively, and a low TW index of 3.23±0.75 and 3.24±0.92, respectively. TR index values for all types of ridges are at moderate levels. Upper slopes and open slopes covered 12.36 and 46.56% of the total area, with a mean elevation of 272.29±72.53m and 233.67±49.17m, respectively. Slope value varies from 19.48±10.88° and 25.21±9.74° with higher values of aspect, southern exposure but moderate values of TW and TR. In these slope positions, the area receives higher exposure to strong wind and solar radiation resulting into a lower wetness index value. As explained in an earlier study, a wetness value below 6 is categorized as a dry site with divergent landforms (ridges and upper slopes). TW index above 7.5 could be dry or wet sites with convergent landforms (lower slopes/flats and depressions), depending on rainfall and evaporation (McKenzie et al. 2000).

Plain surface covered only 1.41% of the total area with a mean elevation of 221.39±35.45m, a very low slope of 2.29±1.71°, a high aspect value of 173.66±115.16°, a low TR index at 1.07±1.22m but shows a high wetness variance at 7.99±3.56. Once again, a high wetness variation might change depending on rainfall and evaporation. Of the total area, valleys covered 7.26% with a mean elevation of 108.63±78.54m. Moderate slope, aspect, and ruggedness describe the mentioned sites. The TW value is 5.38±3.80 shows moderate to high level of wetness index. Local ridge and midslope drainage covered 0.48 and 9.05% of the area with a mean elevation of 257.26±70.51m and 227.28±51.10m, respectively. Both of these landform elements have high values of TW at 6.79±2.52 and 6.71±2.84, respectively, as well as high values of TR index at 4.68±2.04 and 4.84±2.19, respectively. Streams were found concentrated at a moderate mean elevation of 132.41±69.86m and a mean slope of 23.49±15.46°. Slope and aspect or solar radiation shows a wide range with the value of 23.49±15.46° and 191.94±104.27°, respectively. The area, however, has a very high variance of wetness and ruggedness, each at 7.93±4.47 and 4.68±3.14, respectively.

The results of correlation analysis are presented in **Table 2-2**. The result indicated that TW factor has a very strong negative correlation with landform classes with a correlation value of -0.86 while TR index is significantly correlated to slope factor with a correlation value of 0.96. The analysis indicated low values of wetness in high ridges and upper slopes where those areas receive higher wind exposure and compacted soils. The results suggested that TW factor could be a very good indicator for site evaluation and forest planning as well as slope level and TR index.

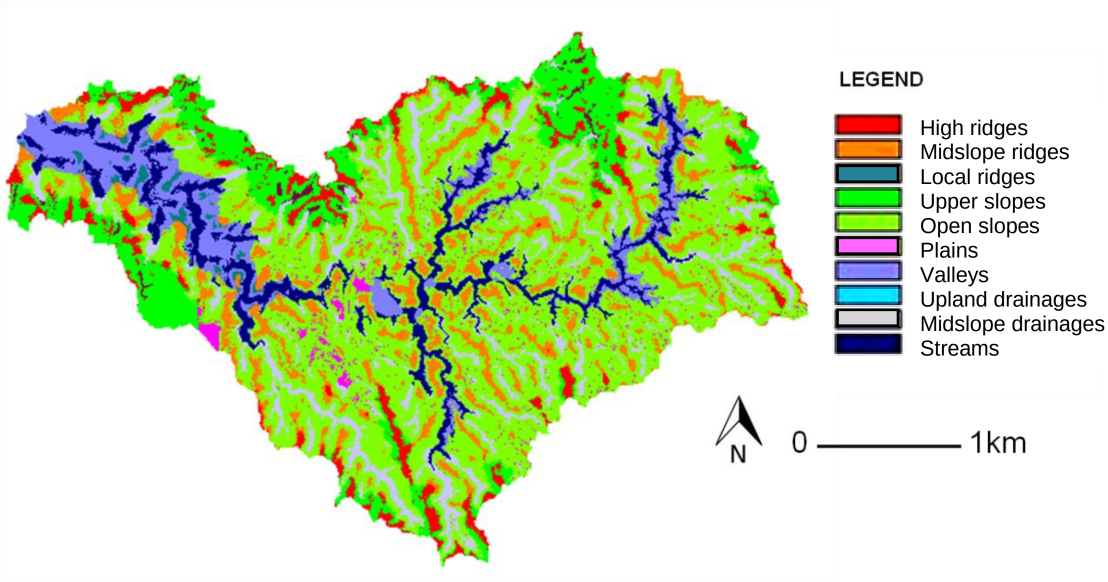
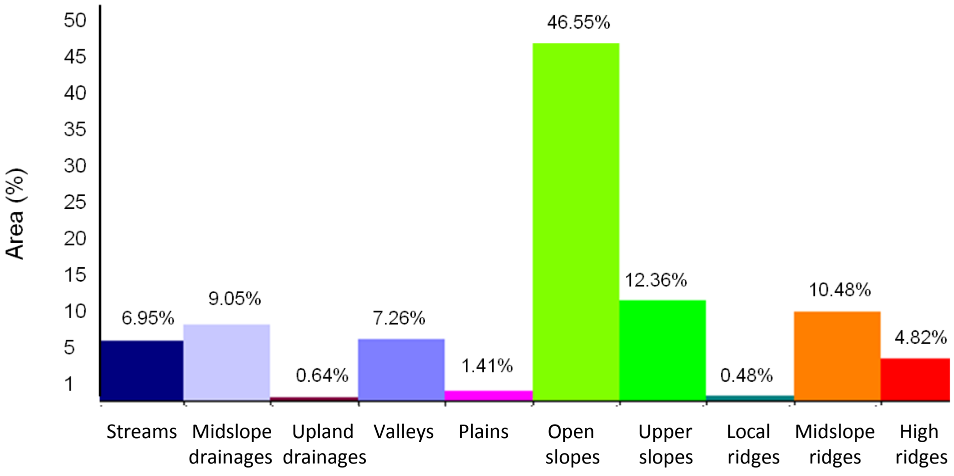


Figure 2-4. Map of landform elements derived from TPI classification analysis



Type of landforms

Figure 2-5. Histogram of landform elements

Table 2-1. Zonal statistic shows mean values and standard deviations of major terrain attributes within the zones of landform classes

Landform class	Area (km^2)	Area (%)	Elevation (m)	Slope (°)	Aspect (°)	TW index	TR index (m)
High ridges	0.52	4.82	292.15±64.33	21.77±9.74	172.46±98.54	3.20±0.81	3.56±1.50
Midslope ridges	1.12	10.48	230.34± 51.36	20.75±8.74	181.05±104.85	3.23±0.75	3.59±1.62
Upland drainages	0.06	0.64	78.93±33.48	29.22±10.88	192.51±108.86	3.24±0.92	4.93±2.36
Upper slopes	1.32	12.36	272.29±72.53	19.48±10.88	194.23±99.12	4.54±1.90	3.28±1.73
Open slopes	5.01	46.55	233.67±49.17	25.21±9.74	188.50±104.27	4.12±1.49	4.12±1.78
Plains	0.15	1.41	221.39±35.45	2.29±1.71	173.66±115.16	7.99±3.56	1.07±1.22
Valleys	0.77	7.26	108.63±78.54	24.63±15.46	201.68±101.98	7.99±3.56	4.27±2.73
Local ridges	0.05	0.48	257.26±70.51	24.06±10.88	197.67±90.52	6.79±2.52	4.68±2.04
Midslope drainages	0.97	9.05	227.28±51.10	26.35±12.03	181.62±103.70	6.71±2.84	4.84±2.19
Streams	0.78	6.95	132.41±69.86	23.49±15.46	191.94±104.27	7.93±4.47	4.68±3.14

Table 2-2. Correlation values show relationship between landform class and terrain variables analyzed in the study

Variable	Landform class	Elevation	Slope	Aspect	TW index	TR index
Landform class	1	0.27	-0.05	0.39	-0.86*	-0.28
Elevation		1	-0.31	-0.48	-0.26	-0.37
Slope			1	0.52	-0.33	0.96*
Aspect				1	0.25	0.57
TW index					1	-0.12
TR index						1

*correlation is significant at $p < 0.0$

2.3.2 Vegetation distribution from NDVI analysis and tree height map

NDVI gives a measure of the vegetation cover on the land surface, differentiating vigorous from less vigorous vegetation (**Table 2-3**). From the analysis, NDVI values for the study site ranges between -1 and 0.77. We found that NDVI decreases with elevation and has a strong influence by slope position. Higher NDVI values (more than 0.40) were detected concentrated near valleys and streams, where tree height is higher (more than 14m). Flat areas and high ridges have lower NDVI ranging from 0.2 to 0.3, covering lower tree less than 8m in height. An NDVI of 0.1, which represents rock, soil, and bare surface, was recorded in the areas near upper slope, open slope, and midslope drainage. The interpretation of tree height and landform type shows similar results (**Figure 2-6**). The differences of NDVI values and dynamic tree height could be explained by several factors. Besides an influence from agricultural use, we have observed canopy opening in some areas as a result of wind effects in open slopes and flat areas, upward to the forested area in higher ridges.

Table 2-3. Characteristics of NDVI signatures

NDVI	Dominant cover
-1.0 ≤ 0	Water, pond, streams
0.1 to 0.2	Bare areas, soil, rock
0.2 to 0.3	Shrubs, grassland, agriculture areas, dry forests
0.3 to 0.6	Dense vegetation
≥0.7 to +1.0	Very dense vegetation, tropical rainforest

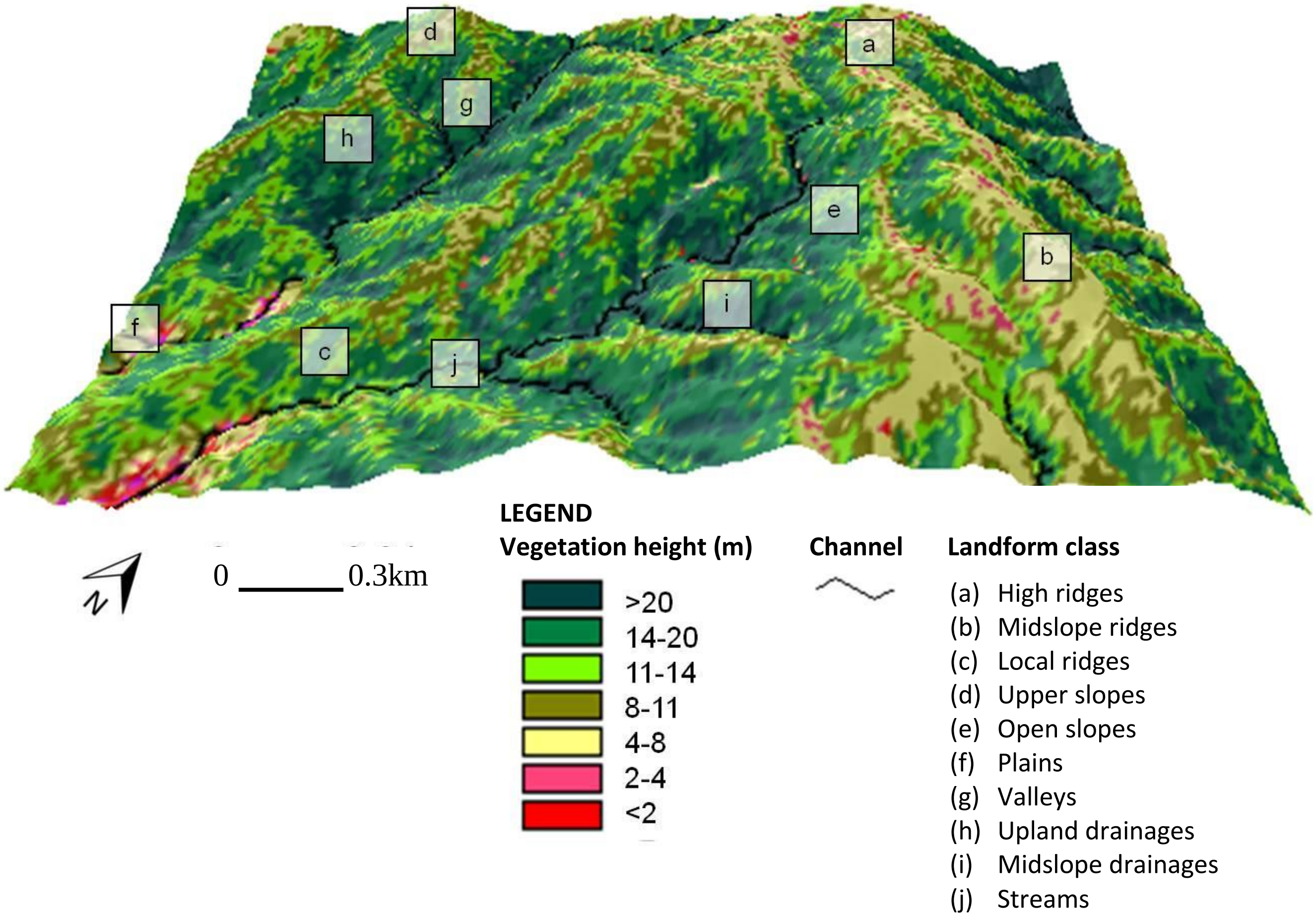


Figure 2-6. Three dimensional (3D) view of tree height map overlayed with landform map explain the relationship between landform type and tree height

TPI and landform pattern contribute a major impact on soils by controlling water and sediment movement. Within the landform shape and structure, lie a very complex terrain features and characteristics. Elevation, slope, and aspect have been demonstrated to be beneficial predictors for the temporal and spatial distributions of variables such as precipitation and radiation; which highly influence vegetation growth and composition (Stage & Salas 2007). TW index is an index which is widely used to explain water level, sediment content, and soil moisture of the area. This index is very important, as it describes soil quality and potential land suitability of certain areas (Wilson & Gallant 2000). TR index is a measure to express the amount of elevation difference between cells in digital elevation grid (Riley et al. 1999). The index explains surface ruggedness or roughness which is a very important variable in selecting an area for development and re-plantation. Alternatively, aspect could be use to explain solar radiation or topographical exposure, described by the symbol ‘θ’, where in complex terrain, θ is not distributed normally (Hauser et al. 1994; Mikita & Klimanek 2010) (**Appendix**-7). In YFA, the topographical index produced an average value between 42° and 60° and shows that the most exposed areas are open areas with mild slopes, plateaus, and mountain ridge, and the least exposed are deep valleys with steep slopes. Open areas with moderate slopes have low values of TW while protected area with dynamic slopes and terrain roughness are described with higher values.

On Okinawa Island, mountains are located near the coast, and the coast facing slopes receive more rain that comes from the humid sea air. The opposite slope receives shadow rain, slower winds, and the climate is drier. There is often a strong relationship among landform, slope position, and soil types which influence the flow of surface water, sedimentation process, wind exposure, and solar radiation, hence affecting the quality and distributions of biodiversity (Blaszczynski 1997). For example, high ridge, plateaus, and steep slopes are frequently covered with shallow and light sandy soils whereas valleys and midslope drainage are often covered with deep and rich alluvial soils. As mentioned by Sai On (1768), flat terrain and gentle slopes are considered to be ranked as the lowest grade for forest growth, where wind exposure is high, there is no barrier of protection, and the area has a high potential for damaging typhoon effects. In this study, this situation was explained by lower NDVI values and low tree heights, as well as low TW index near the mentioned zone. The best locations for afforestation are areas with gentle to moderate slopes, where the surrounding mountains serve to protect and enclose the area from wind exposure, paralleling with Sai On's concept of 'embrace protection'. In Sanrin Shinpi, it is stated that despite soil quality, terrain attributes are the primary factor for successful forest growth. Sai On's observations strongly reflected the natural environments of tropical islands, which are highly impacted by strong seasonal monsoon winds and annual typhoons. Understanding landform characteristics, such as wetness index, terrain ruggedness, and topographic exposure, is important, as it provides beneficial information for effective land management and erosion control processes.

Areas receiving higher exposure to solar and wind are very sensitive, where soil fertility and capacity are reduced to hold the vegetation. Development on these areas should be restricted, as it could cause soil erosion, thus increasing the surface runoff, which could make these slopes prone to landslides. This will indirectly affect the coastal zone and will significantly damage the lower vegetation and influence the aesthetic values. However, this issue could be controlled by planting wind resistance trees along the sensitive sites. A study by Duryea and Kampf (2007) recommended a list of proven wind resistant tree species for tropical and subtropical forest types. In the case of Okinawa Island, *Garcinia subelliptica* (Common name: Fukugi) was proven to have high adaptability, capability, and strong wind resistance, and planted as landscape trees as well as to serve as a wind protection barrier especially in traditional villages and along the lower coastal zone (Chen & Nakama 2011).

Table 2-4. Description of landform classification and proposed forest functions discussed in the study, providing references from Sai On (1768), Arnot & Gallant (1981) and Köhler & Breu (2005)

Landform elements	Slope level	Propose land use
High ridge, Upland drainage	Extreme slope	Protection, conservation, ecotourism, education
Local ridge, Midslope drainage	Moderate to strong slope	Agroforestry, commercial forest
Midslope ridge	Moderate slope	Timber harvesting (with strict conservation measures)
Upper slope, Open slope	Moderate to strong slope	Agroforestry, protection, education
Plain, Plateaus	Flat areas to gentle slope	Lowland farming, agriculture, plantation
Valley	Moderate to low slope	Agroforestry, commercial forest, ecotourism
Stream	Moderate to low slope	Agroforestry, commercial forest, conservation

Landform and terrain characteristics strongly influence forest health and vegetation pattern. The statement was strongly emphasized in both studies, previously by Sai On's observation and currently by geospatial evaluation. It is agreeable that independent results obtained from digital terrain analysis are not sufficient enough for site evaluation and land use planning. Additional information on abiotic environment (i.e., soil type, geology, forest cover) of the specific study area is required for a concrete and precise land assessment. The application of geostatistical techniques within SAGA GIS provides comprehensive, multifunctional, and user-friendly modules that are very effective for geoscientific analysis and DTM computation especially for large regions (Conrad 2006). Supported data from satellite images or remote sensing will improve the evaluation, but the lack of environmental information may be supported through predictive terrain modelling in geospatial applications (Thwaites 1995). Terrain analysis and classification based on DTM is very cost effective and time saving, as it provides basic but important information for rational land use especially for developing countries that are under severe environmental and economical constraints.

2.4 Conclusion

The landform classes obtained from the analysis differentiate dynamic terrain characteristics in YFA. The presented results and discussion integrated the geospatial approach and a traditional concept of forest terrain. The paper provides an interesting outlook of historical concepts and its re-interpretation using modern approach. By deep understanding of the terrain characteristics, potential and specific constraints of the forest could be detected. Information and methodology discussed in this paper will be valuable for landscape and suitability studies especially at regional level.

Chapter II is adapted and restructured from Azita Ahmad Zawawi, Masami Shiba, Noor Janatun Naim Jemali. 2014. Landform classification for site evaluation and forest planning: Integration between scientific approach and traditional concept. *Sains Malaysiana* 43(3): 349- 358

Chapter III

Simulation of Terrain Attributes from LiDAR Data for Slope Failure Hazard Assessment in Steep Forest of Okinawa Island

3.1 Introduction

Erosion and/or failure of slope being due primarily to forest road construction activities has become long-term key issues in Okinawa Island as it demands special techniques and high cost for its recovery and maintenance. Early detection and identification of hazardous sites correlated with slope failure is important for forest road network and drainage system planning.

The development of erosion is very complex and unpredictable where traditional mapping and inventory do not promise sufficient and satisfactory results (Fulajtar 2001). Erosion often occurred at specific location under several environmental correlates such as geology, topography, climate and vegetation (Walker & Shiels 2013). Kurahashi et al. (2008) studied that besides rainfall, slope failure was the most abundant and constituted 81% of natural disasters. Many factors including human-induced land alteration can cause slope failure and impacted the surrounding area depending on the type of landslide hazard (Gibo et al. 2008). Having insufficient or limited data is a common problem at the assessment level. To solve this issue, there are two solutions which are i) invest high cost and labour to get updated and sufficient data or ii) using computer simulation and spatial analysis to predict potential hazard before site assessment been done.

Hazard prediction studies and mapping using GIS was introduced as early as 1970 by Radbruch, and the study was then extended by many researchers across the continents. Among the pioneers are Lee and Min (2001), Montgomery and Dietrich

(1994), Pike (1988) and Mitasova et al. (1996) who recently introduced the potential of topographic parameters in simulating and predicting erosion. In Japan recently, Ayalew and Yamagishi (2005), and Sato et al. (2002) were among those who popularized the application of GIS in developing slope failure and landslide map. However, Carrara et al. (1999) raised an issue where he emphasized the importance of knowledge and understanding the underlying causes behind the disaster development. Guzetti et al. (1999) reviewed that, parallel with the advance development of geospatial technology, third world countries still facing a conflict in controlling natural hazards due to high cost of engineering works and major land use planning. A system that is efficient, easy to use, flexible and reliable should be introduced, especially for foresters with lack of technical skills to operate spatial data.

In Okinawa Island, slope failure associated with forestry-related activities such as road construction has become a long term problem which demand high cost for maintenance and road re-construction. Several studies were done in Okinawa on characterizing the soil strength as well as landslide type (Chen et al. 2007) and the difficulties to predict the hazard have been arise (Hiramatsu et al. 2013). Early detection of hazardous sites correlated with slope failure is important for forest road network and drainage system planning. Lack of historical data and difficulty to assess the forest area become major constrain for site assessment and evaluation. Nowadays, the development of high resolution satellite data and remote sensing is very effective to overcome this problem.

The aim of this study was to introduce a method to identify and to map slope failure hazardous sites using digital terrain simulation. In this paper, several terrain parameters that have strong influence to the development of erosion are discussed and computation methods to derive the potential slope failure hazard map are presented.

3.1.1 Definition of terminology

In this paper, three main terminologies are frequently used, which are; erosion, slope failure and hazardous site. Referring to the philosophical approach taken by USDA-Soil Conservation Service, erosion is defined as a natural geomorphic process of the forest ecosystem which includes processes of weathering and the removal of soil particles by several factors, which are wind, water or other weathering agents (Wischmeier & Smith 1965) Increasing erosion can cause severe impacts on forest and watershed area by increasing sedimentation, degrading water supplies, and loosen the vegetation strength towards its soil and root holding system which will gradually contributed to cause slope failure. The effect of erosion depends on the type of erosion processes and its magnitude, and there are various terms to describe erosion effects.

According to the International SABO Association, slope failure is defined as a phenomenon where a slope collapses gradually resulting from weakened self retainability of the earth. As we use the term here, the phenomenon involves downhill soil failure or mass influenced by slope modification and heavy rainfall especially at sensitive and erosive site. This term is widely used in this paper to explain the slope instability damage resulted from severe erosion in the study site. The third important term used in this paper is hazardous. In this context, hazardous zone refers to an area where erosion may potentially result in damage to a resource or loss of property. The hazard map produced indicates areas of initiation of slope failure. Special considerations and alterations to this area are needed to prevent adverse effects to the forest condition.

3. 2. Materials and methods

3.2.1 Study area

The study site was characterized by moderately sloping to steep rolling terrain ranging from 0° to 68° (**Figure 3-1**). The examined area covers 246.8ha of the total forested areas and has a highly diversified georelief as well as high species richness. Forest road networks were extensively constructed in 1977, enhancing forestry activities and land conversion in mountainous areas (Takashima et al. 2008). Exposure to monsoonal typhoon, heavy rainfall, road construction on steep terrain, as well as forest utilisation influenced slope failure in the study area (Yamashiro 2005). This type of forest area requires intensive conservation measures to prevent further forest damage. Geographical location of potential hazardous areas is very important information required for both forest operation activities and conservation planning.

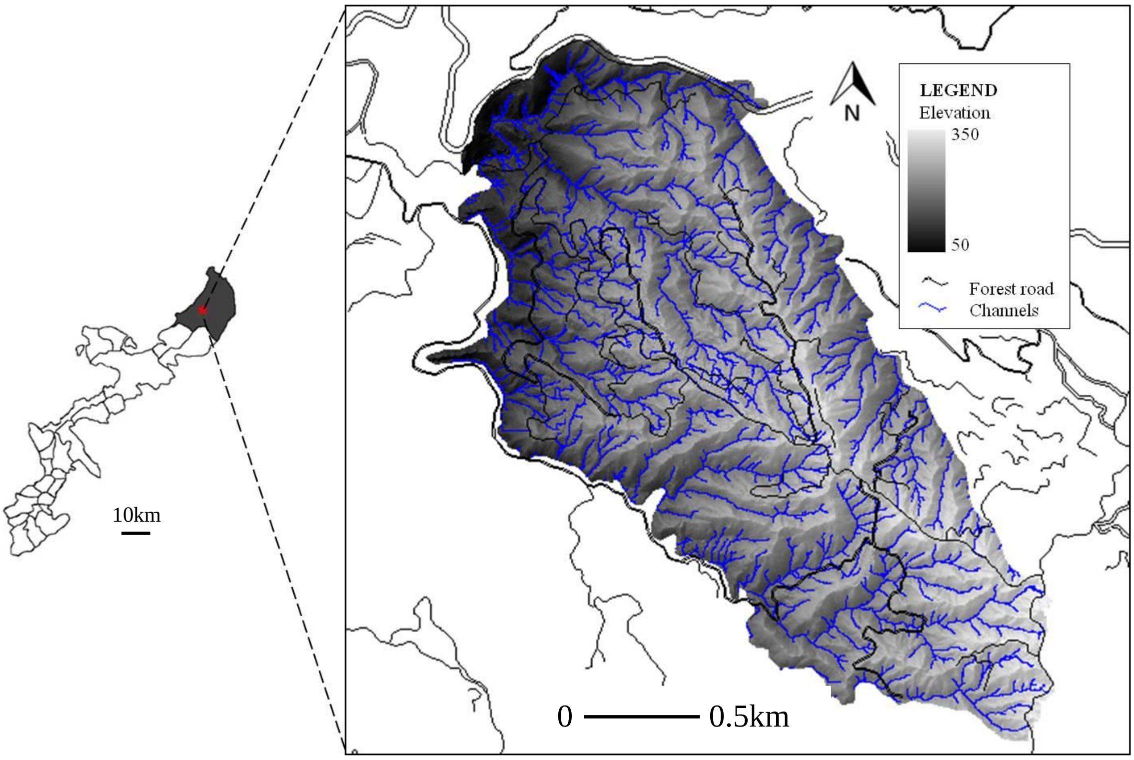


Figure 3-1. Overview of the study site located within YFA

3.2.2 LiDAR data processing

The study used DTM and DSM derived from Light Detection and Ranging (LiDAR) data at 1m x 1m resolution, obtained from The Geospatial Information Authority of Japan with cooperation from The Department of Agriculture, Forestry and Fisheries of Okinawa (**Figure 3-2**). LiDAR data specification is presented in **Table 3-1**. Topographic analysis and simulation were done within SAGA GIS software and ArcGIS 9.3. The study was done following three main steps; i) topographic analysis, ii) vegetation cover assessment and iii) weighted overlay analysis. Research framework is summarized in **Figure 3-3**.

Table 3-1. Flight and sensor parameters of LiDAR

Variable	Characteristic
Sensor type	ALTM 3100 (CASI -3)
Digital camera type	DSS Model 300
Laser wavelength	1064nm
Scan frequency	39Hz
Scan angle	±20°
Flight altitude	1100m
Footprint size	0.2mrad
Date recorded	April 2011

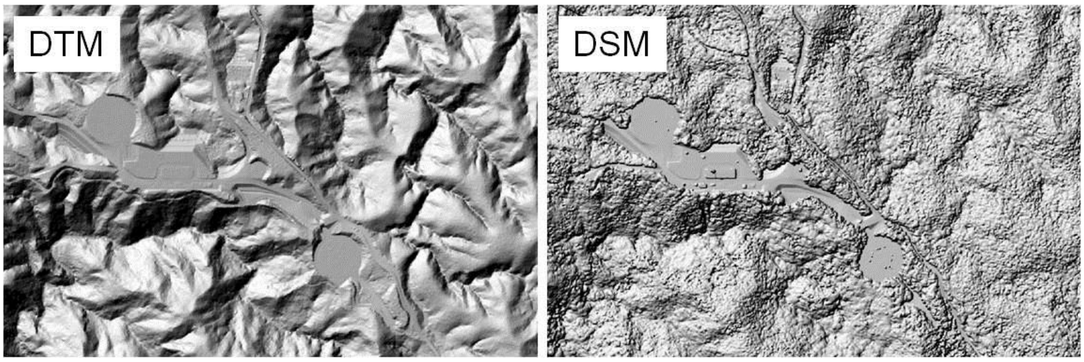


Figure 3-2. DTM and DSM derived from LiDAR

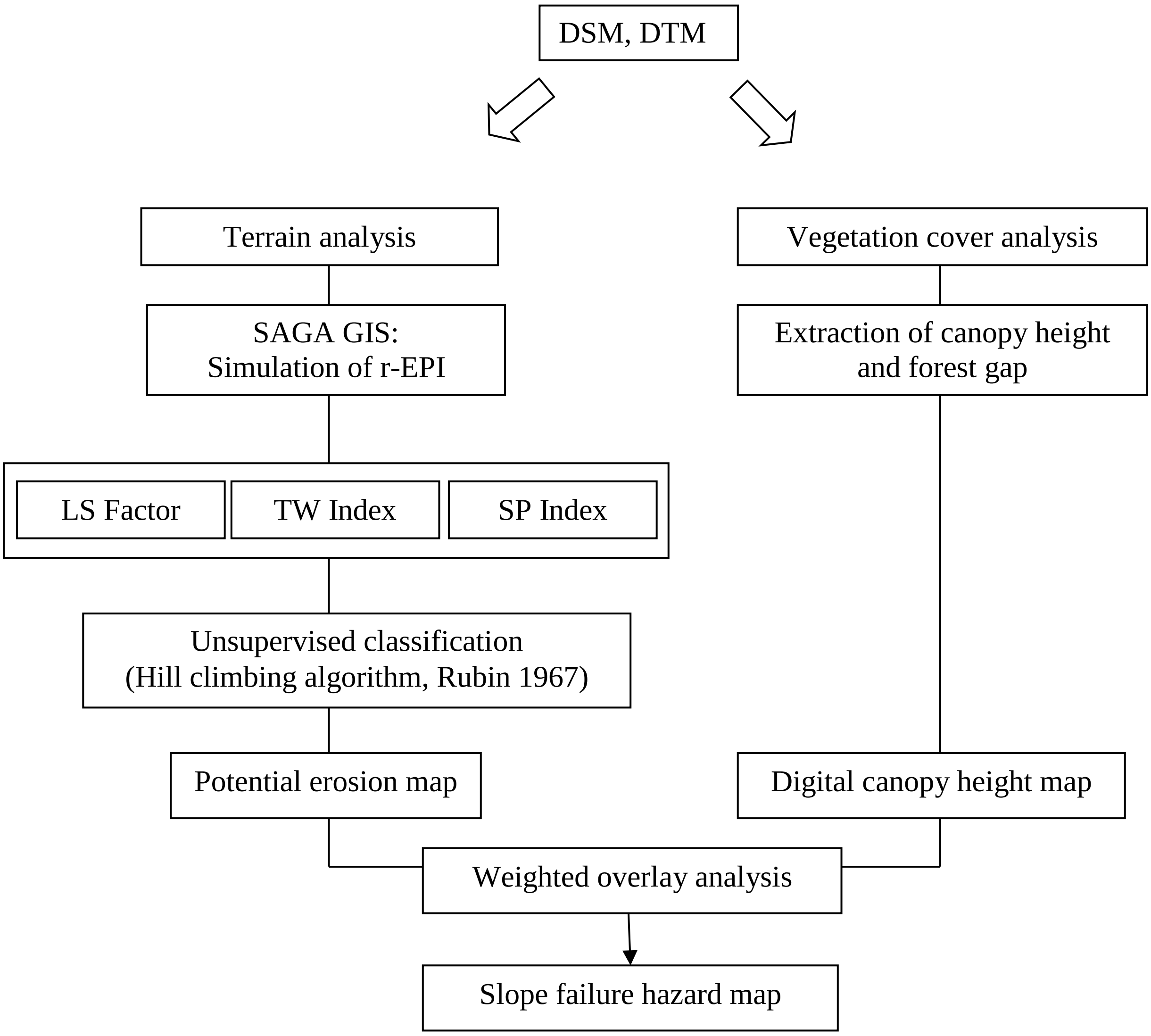


Figure 3-3. Research framework of data processing within GIS

3.2.3 Terrain analysis

The first step was performed through detail morphometric analysis of DTM using SAGA GIS software to derive primary terrain attributes which are slope, catchment area and aspect. These parameters which were studied to have most influence on erosion development were simulated using numerical expressions to produce secondary terrain attributes namely Erosion Potential Related Indices (r-EPI). The result of r-EPI are slope length-gradient factor (LS factor), topographic wetness index (TW index) and stream power index (SP index), respectively. The factors are as described below:

Slope – Length Gradient Factor (LS factor)

Slope angle and slope length are the most important parameters in slope stability and is directly related to erosion rate and processes (Saha et al. 2005, Yalchin 2008). LS factor demonstrates the fact that erosion increases with slope angle and slope length (Rodriguez & Suarez 2010). Many erosion models including the Universal Soil Loss Equation (USLE) used LS factor as a parameter to calculate the influence of terrain on potential soil loss and deposition. In this study, LS factor (dimensionless) was computed by applying topographic indices module in SAGA GIS following a numerical model developed by Moore and Burch (1986) expressed as:

$$\text{LS factor} = (A / 22.13)^{t} \, (\sin\beta / 0.0896)^{1.3}$$

where A : slope length in meter, t : constant dependent of slope value and β : slope angle in degree.

As been studied by Mitasova (1996), the index corresponds to area with the highest probability of erosion. Topographically, higher values of LS factor are found in steep slopes and complex contour near river banks and cliffs.

Topographic Wetness Index (TW index)

TW index represents the topographic control on soil wetness and corresponding to soil water content (Gallant & Wilson 2000). This factor is important as the soil water content is one of limiting factors for plant growth and is also a factor in soil formation (Moore et al. 1991). In this study, the equation was applied as the study site consists of uniform soil properties where transmissivity is assumed to be constant along the catchment. Values were formulated as:

TW index = In (A_s / tan β)

where A_s : Catchment area (m^2/m) , β : slope in degree

TW index was constructed by considering two shapes of slope; concave and convex. Concave slope in low gradient areas will gather water and have low value while convex slope in steep area will shed water and contribute to higher TW index.

Stream Power Index (SP index)

Moore and Wilson (1992) studied that SP index was used to explain potential flow erosion and related hydrological landscape processes. The calculation considered both site location and local slope geometry in the landscape combining data on slope steepness and specific catchment area. As specific catchment area and slope steepness increase, the amount of water contributed by upslope areas and the velocity of water flow increase, hence SP index increase and erosion risk increase (Florinsky 1998).

The index was expressed as:

SP index = $A_s \tan \beta$

where A_s : Catchment area (m^2/m) , β : slope in degree

For terrain analysis, an unsupervised classification method was done to all three variables to define their spatial similarities following hill climbing method (Rubin 1967). Normalization was done to all raster data to rescale the values. For effective interpretation, number of classes was set to five by applying the user-defined class identifier. The output raster was a potential erosion map.

3.2.4 Vegetation cover assessment

The purpose of this step was to distinguish ground types and forest cover in the study site. As information on vegetation cover is very beneficial to represent stand density, the existence of forest gap or bare ground reflects its site quality related to disturbance on the specific area. Using LiDAR data, type of vegetation cover can be differentiated from the tree by considering a low height range (Antonarakis 2008). For this objective, DSM was subtracted by DTM and a Digital Canopy Height Model (DCHM) was obtained. Vegetation and ground separation was carried out using SAGA GIS. Gaussian filtering was done to remove unwanted noise. Using the height level separation method following (Koarai et al. 2010), only basic land cover classes were analysed, and this process resulted five classes of land cover categorized by tree height value namely bare areas, low, middle, high and very high.

3.2.5 Weighted overlay raster combination

Potential erosion map value and digital canopy height map value were combined using weighted overlay analysis in raster calculator application within ArcGIS 9.3. Both maps were set to similar numerical ranking system from 1 to 5, where the highest rank; Class 1 represents area that is very severe to slope failure and lower rank highlights area that is less prone to slope failure. Percent of influence were set to 75% for terrain factor and 25% for vegetation cover factor. The cell values of each input raster are multiplied by the raster’s weight and the results are added together to produce the final output raster. Weighting values were assigned using subjective approach through often discussion and interview with forest officers of the Okinawa Department of Agriculture, Forestry and Fisheries and officers from Kunigami Village Office. Based on documented evidence of previous slope failure events (Higashi et al. 1985, Okinawa

Department of Agriculture, Forestry and Fisheries 2010, Sidle & Ochiai 2006, STFRJ 2010) the experts claimed that topographical characteristic has more influence on slope failure in Okinawa Island and suggested a weighting ratio of approximately 3:1 between terrain factor and vegetation cover factor. This method was called a heuristic evaluation method where it allows the determination of weighting factors based on the experience of forest officers involved. This method entails a substantial degree of subjectivity but is practical and acceptable when there were limited ground truth data for statistical analysis. The overlay analysis resulted a final map, namely slope failure hazard map.

3.2.6 Ground truth inspection and field verification

Field verification was done in three phases. First phase was done through visual assessment based on mutual comparison of readily documented slope failure map produced by the Okinawa Department of Agriculture, Forestry and Fisheries. Second phase was a ground truth inspection on selected test site in the study area, and third phase was a visual comparison to aerial photo. Due to the difficulty to assess dense forest of the whole study area, Yona forest road was chosen for site inspection and comparison as the inspected road has a severe history of slope failures. Site inspection was done two times, dated October 2012 and January 2013. Using previously documented map as reference, coordinate for each slope failure found along the forest road was recorded and was later transferred to GIS geodatabase. A Garmin GPS model Oregon 550 with coordinate reference WGS 84 Zone 52N was used for this task. Individual position, length, width and photo on each observed points were recorded. Each slope failure points taken from ground inspection were draped over the simulated erosion hazard map and manually compared within ArcGIS 9.3. ArcGIS spatial analyst was effectively used in this process.

3.3. Results and discussions

3.3.1 Map interpretation

Secondary terrain attributes derived from the morphometric terrain analysis are slope-gradient factor (LS factor), topographic wetness index (TW index) and stream power index (SP index), respectively (**Figure 3-4**).

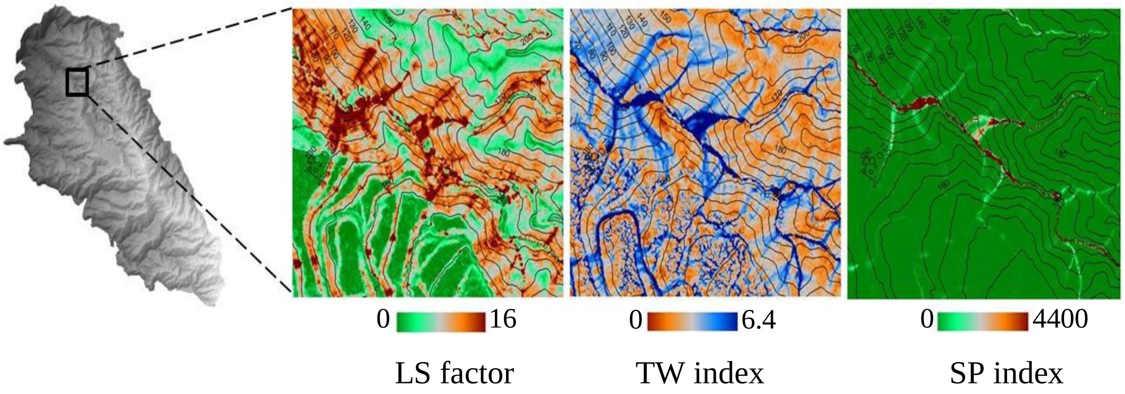


Figure 3-4. Secondary terrain attributes which are LS factor, TW index and SP index show higher values on steep slope

Three maps were produced from the analyses which are potential erosion map, digital canopy height map and slope failure hazard map, respectively. Detail interpretations of each map are as discussed below.

Potential erosion map

Unsupervised classification done to all the tree variables produced a new raster namely potential erosion map, in which the study site was divided into five classes of erosive rate (**Table 3-2**, **Figure 3-5(a)**). Class 1 which covers 0.1% of the total study site showed the highest value of LS factor, SP index and TW index which are 21.3±6.3, 2222.6±1425.7m^2/m and 8.4±1.0, respectively. High value of LS factor suggested higher rate of soil loss and lower value shows opposite definition. The result presented that more than 40% of the total study areas showed value of LS factor more than 10, suggesting area with higher erosive rate and have high tendency to develop slope failure. On the other hand, TW index describes the tendency of runoff dispersion in the watershed; which high value shows the erosional sites (Wilson & Gallant 2000). Class 5 shows a very low value of LS factor but moderate value in TW index and SP index which signified that the detected sites consist of flat terrain, less sensitive to erosion and topographically stable.

Table 3-2. Class, area, mean value and standard deviation of r-EPI derived from the analysis

Terrain stability class	Area (ha)	Area (%)	LS factor	SP index (m^2/ m)	TW index
1	0.2	0.1	21.3±6.3	2222.6±1425.7	8.4±1.0
2	6.4	2.6	14.4±4.4	343.5±240.6	6.5±1.2
3	98.0	39.7	10.3±2.0	26.0±21.5	3.2±0.8
4	99.5	40.3	5.4±2.3	4.0±2.6	2.3±0.7
5	42.7	17.3	3.3±2.5	15.0±24.0	4.8±1.2

Digital canopy height map

Table 3-3 and **Figure 3-5(b)** shows the result of vegetation cover assessment which differentiates ground types as well as forest cover in the study site. The map produced from the analysis was re-classified into 5 classes which are bare areas, low vegetation, middle vegetation, high vegetation and very high vegetation, respectively. Vegetation removal on a slope decreases support for the soil and surface material, especially on the cut bank of a stream where continuous erosion processes will contribute to slope failure.

Table 3-3. Ratio of vegetation cover classification categorized by canopy height level derived from DSM and DTM of the LiDAR data

Class	Canopy height (m)	Description	Area (%)
1	0 – 0.5	Bare / Very low vegetation	2.5
2	0.5 – 1.5	Low vegetation	1.2
3	1.5 – 6	Middle vegetation	9.0
4	6 - 15	High vegetation	62.8
5	>15	Very high vegetation	24.5

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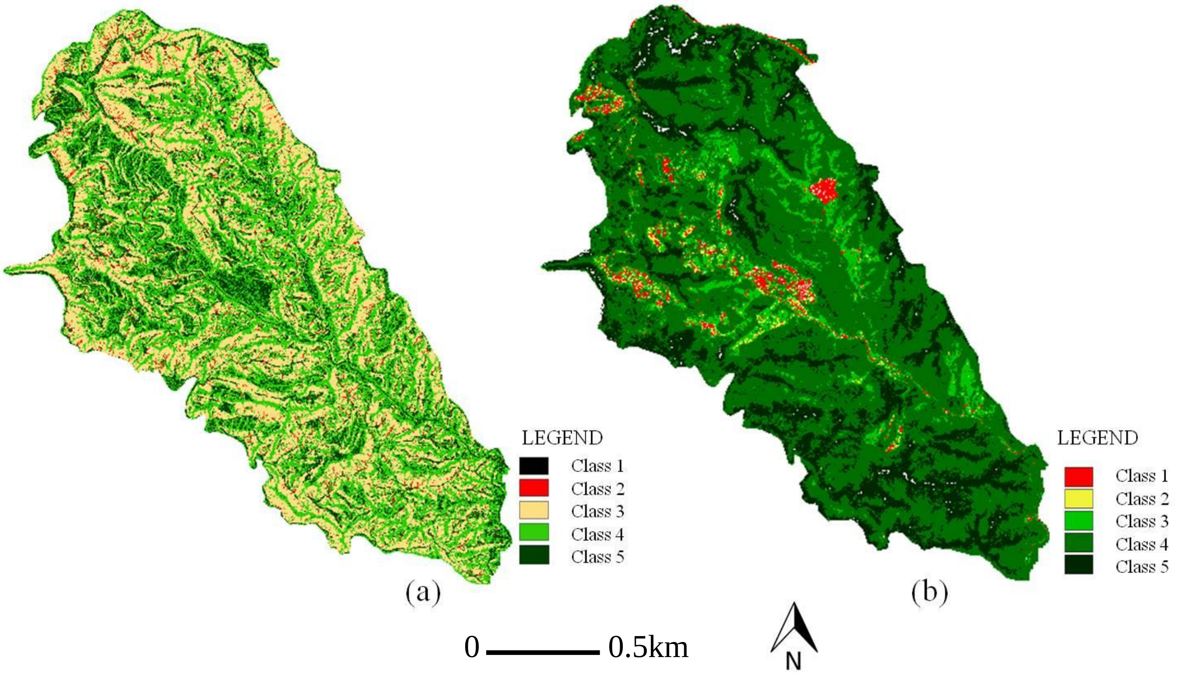


Figure 3-5. Two main indicators for erosion hazard assessment which are terrain factor and vegetation cover factor illustrated by: **(a)** Potential erosion map **(b)** Digital canopy height map

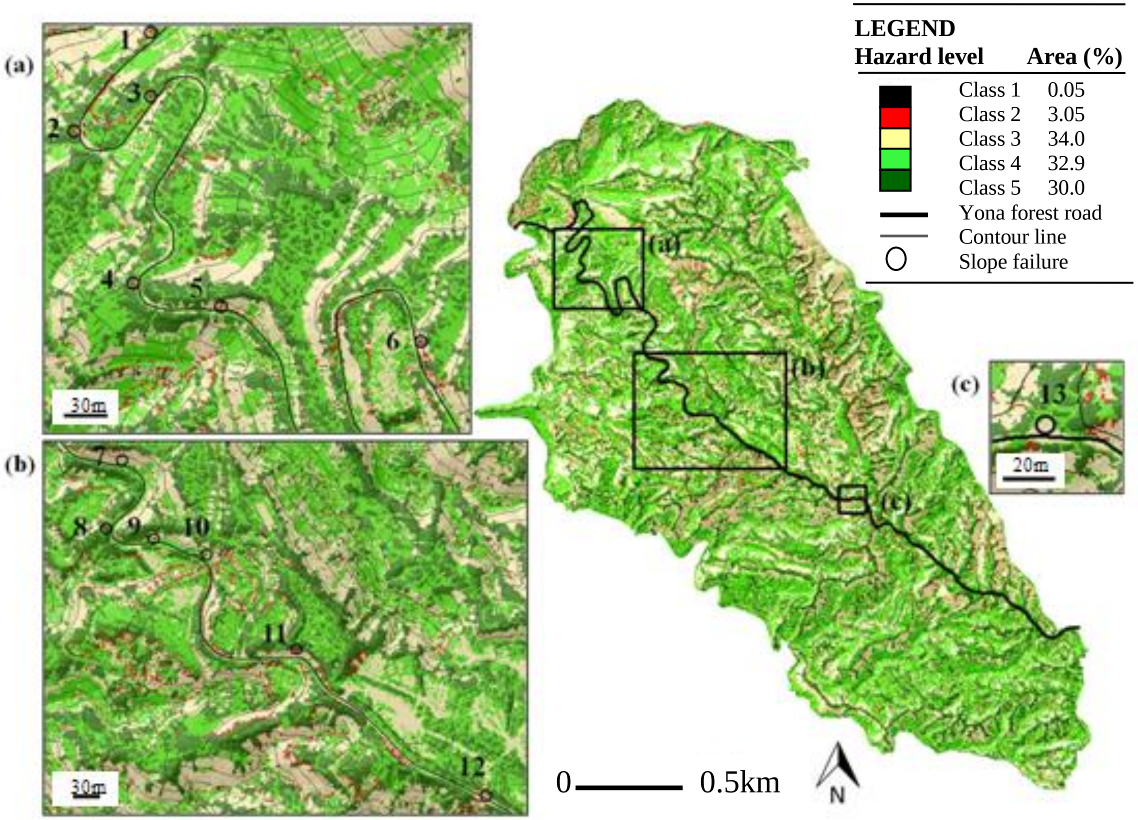


Figure 3-6. Slope failure hazard map showing hazardous sites

Note) Class 1 indicates most hazardous site and Class 5 very low hazardous site

Figure (a), (b), and (c) present larger views of slope failure points observed along Yona forest road

Slope failure hazard map

A hazard map refers to a map describing the areas at risk of disaster. The slope failure hazard map resulted from the data integration is presented in **Figure 3-6**. The map is described using ranking system from 1 to 5, where the highest rank; Class 1 highlights area that is very hazardous and lower rank presents area that is less hazardous, mostly found on flatter terrain and simple slopes. Class 1 and Class 2 which suggested hazardous sites are concentrated on steep slopes and are mostly characterized with lower canopy cover. Both classes cover 3.1% of the total study area, while Class 3, Class 4 and Class 5 each covers 34, 32.9 and 30% of the study area, respectively.

3.3.2 Comparison with ground truth inspection and field verification

Inventory data on Yona forest road recorded 13 slope failures, and 11 of the detected point's fall within the hazardous sites (Class 1 and Class 2) in the simulated slope failure hazard map. **Figure 3-6 (a)**, **(b)** and **(c)** present larger views of hazardous points observed along the forest road. The comparison showed accuracy value of 84.6%.

In addition to the site inspection, aerial photo interpretation throughout the study area has observed several slope failure scars. It is noticeable from the photo that most of the visible damages, which were distinguished by the recognition of barren ground, were concentrated along/near the forest road and in steep slopes (**Figure 3-7**). Severely eroded sites were visually detected by lighter colour of its surface as a sign of exposure and vegetation loss. Site inspection however has observed that some of the scars were now revegetated, mostly by succession species. Readily documented map and site inspection suggested that most of the damage scales are small; with the maximum slope failure reached 20m width and 25m length. Visual interpretation from aerial photo did not sufficiently detect small scale slope failures below the canopy cover. However, it provides beneficial information to distinguish true damage and false damage; which were not associated with slope failure, such as forest opening due to agricultural activities or timber harvesting.

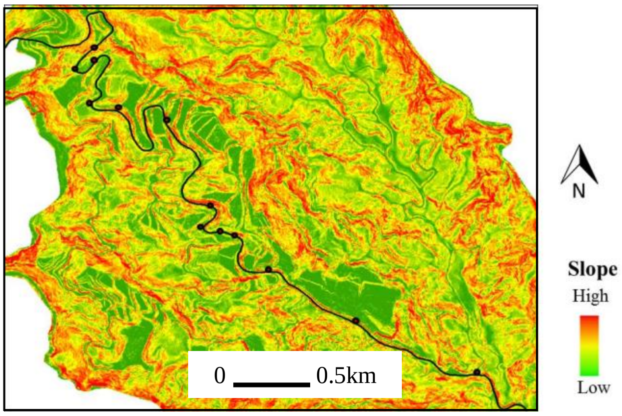


Figure 3-7. Slope condition map along Yona forest road

Figure 3-8(a) shows typical type of slope failure in the study site occurred very near to the forest road, and **Figure 3-8(b)** shows a common view along the observed Yona forest road where retention wall was constructed at hazardous site for stabilization purpose. The concrete wall was built on the lower part of the slope to suppress a collapse and also to prevent the movement of eroded soil downwards.

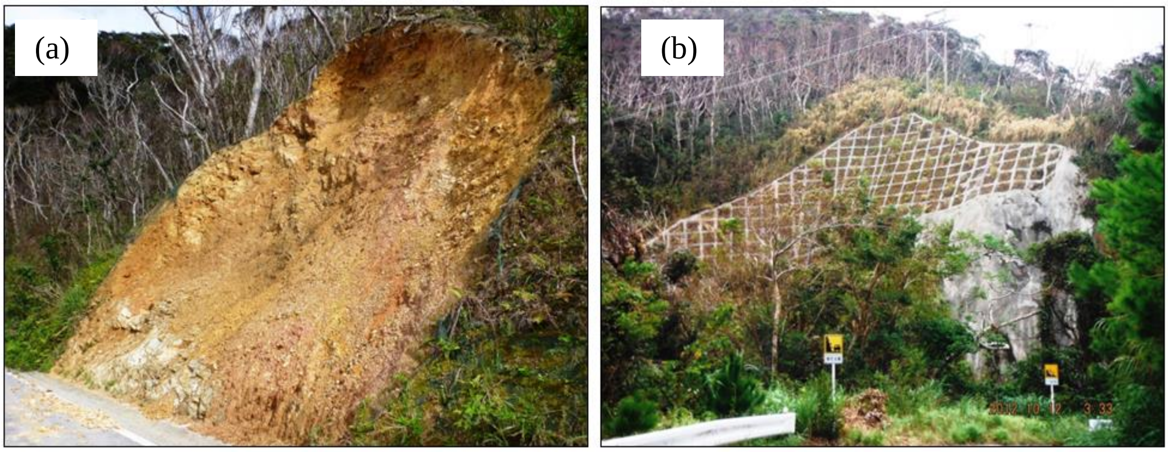


Figure 3-8(a) Typical slope failure observed within the study site leads to severe vegetation removal and **(b)** the erosion hazardous site was constructed with retention wall for stabilization purpose

3.3.3 Characteristics of slope failures

Table 3-4 describes the characteristics of each slope failure recorded along the inspected forest road. From the 13 slope failure points, 8 points fall in the Class 2 of the terrain stability classification, 4 points fall within the Class 3, and 1 point fall in Class 4 which suggested a stable slope. It was observed that almost all erosive sites detected recorded LS factor value above 10. As been studied since decades ago, steeper slopes have been proven to have greater influence on slope instability. Constructed road at steep slopes change the terrain condition, increased LS factor, decrease loads on the toe slope and influence stability. Higher LS factor will significantly increase the risk of erosion. At sensitive and erosive site, poor constructed slope are easily affected by water movement which will lead to continuous problems of erosion. These factors were both explained by the high value of SP index and TW index measured within the hazardous sites. The combination of subsurface water from storm flow and steep slopes will trigger erosion by developing pore water pressure, affecting soil moisture content and root strength to hold vegetation (Sato et al. 2002). Strong attention should be given to these areas as it has very high potential to collapse. Damages were categorized into two main types which are i) cutting slope collapse and ii) shoulder and/or fill slope collapse. In several points, soil debris were found to be piled on the lower slopes and gathered at the road side.

Information in **Table 3-4** clearly shows the role of vegetation cover as the terrain stabilizer. As an example, even though Point 3, Point 4 and Point 12 were classified as moderately stable (Class 3) in the terrain stability class, less vegetation support on its slope surface had increased the hazard risk and finally caused slope failures (Class 2 in the slope failure hazard map). Point 9, with terrain stability Class 2 and vegetation cover Class 1 was finally evaluated as hazard level of Class 1. Referring to the table, although

Point 9 was characterized by low value for both LS factor and SP index (each at 7.9 and 87.4m^2/m, respectively), the TW index was considered high at 7.9. A high value of TW index combined with less vegetation cover might have contributed to the severe hazard. As been proven, hazardous erosion usually found in or near forest gaps created by tree gap affected by typhoons, corresponds to the area covered by low vegetations (herbaceous, grass, bare ground) and on very steep slope. Vegetation cover plays an important role as terrain stabilizer to increase the slope stability. Areas of steep slopes which were earlier detected as erosive but were later found to be covered with higher abundance of vegetation are less prone to severe erosion while areas with gaps received opposite effects (Mizuhara & Ohte 1983).

The three dimensional visualization presented within GIS tools clearly shows that leeward slopes had fewer damage as it its drier than windward, especially when experiencing strong typhoons and heavy rains. This condition was influenced by TW index on the specific site. In addition, removal of vegetation along the slopes will increase saturation risk and cause slope failure. Considering to this, further forest opening and land development on these sensitive areas should be restricted.

Two detected slope failure points recorded during the site inspection (Point 7 and Point 13) showed no mutual similarities to the simulated hazard map. However, these two points were observed to be located very near to the hazardous site in the slope failure hazard map.

Table 3-4. Characteristics of slope failures recorded along the inspected forest road

Slope No.	Erosion Potential Related Indices			Terrain stability class	Vegetation cover class	Hazard level class	Type of failure
	LS factor	SP index (m^2/ m)	TW index				
1	11.7	136.1	6.1	2	1	2	Shoulder and/or fill slope collapse
2	12.5	241.5	4.2	2	1	2	Cutting slope collapse
3	9.3	57.3	4.0	3	1	2	Shoulder and/or fill slope collapse
4	9.9	77.0	6.6	3	1	2	Shoulder and/or fill slope collapse
5	10.3	47.7	5.9	2	3	2	Cutting slope collapse
6	10.9	135.9	5.2	2	2	2	Cutting slope collapse
7	12.6	33.0	3.4	3	4	3	N/ A
8	11.8	189.4	6.3	2	3	2	Shoulder and/or fill slope collapse
9	7.9	87.4	7.9	2	1	1	Cutting slope collapse
10	10.1	247.6	8.1	2	4	2	Cutting slope collapse
11	10.6	59.3	7.3	2	1	2	Cutting slope collapse
12	11.1	25.1	4.9	3	1	2	Shoulder and/or fill slope collapse
13	2.6	5.7	6.4	4	2	3	N/ A

Note) N/A: Not Applicable

3.3.4 Influence of terrain to erosion and slope failure

Our site investigation has observed that artificial slopes such as cut slopes are clustered along the forest roads, and are included in the hazardous zone. All cut and exposed areas created by manmade slopes have significantly increased the slope angle; therefore intensive care and special design are required, as they are very sensitive and susceptible to instability. In contrast, a well constructed slope with proper maintenance is more resistant to damage since the soil is in good compaction and more stable. In the case of Okinawa, roads were built on steep slopes in mountainous terrain and forest production taken place near mountain ridges. Slope stabilization effort concentrates on improving the slope drainage and by constructing retention wall as a physical restrains to cover the slope and underlying bedrock using chicken wire or bolting rock. Constant failures of the steep slopes require that the similar road be repaired frequently.

In this paper however, we will not discuss in detail about this factor as our main focus was to introduce a method to identify slope failure hazardous sites using digital terrain simulation, in which the artificial slopes are included in the computation. Identification of potential erosion and recognition of hazardous area is very important to improve preventive method. Other than traditional inventory, GIS analysis was proven to play an effective role as a measure of estimating spatial variations of erosion through the study of terrain influence on surface changes (Bohner & Selige 2006). It is agreeable that rainfall and climatic factors play an important role in the indices calculation. Adequate data on rainfall intensity and water flow will produce more accurate result. In this study, all simulation was done with the respect that the study area receives uniform rainfall and consists of homogenous soil type.

When erosive and hazardous sites are identified, an understanding of their interactions and processes need to be clarified. Integration of high resolution data and advance GIS approach allows three dimensional terrain simulations which is very effective to improve our visualization and understanding related to topographical processes. Digital terrain analysis has huge capability to provide insight of the terrain types and processes. Lack of environmental and ecological information could be explained with the optimum use of high resolution LiDAR data as well as extensive supporting data from previous studies.

The analyses and results discussed in this study focused on the influence of terrain factors on erosion by the detection of its potential hazardous areas and do not consider time and intensity of the disaster. Studies of erosion, slope failure and monitoring could be very complex and time demanding. Deep understanding of its processes and controlling factors is important to help forest planners and managers to make decisions regarding site suitability. Climatic factors, details geological and soil factors as well as detail hydrological modelling could be integrated to improve the evaluation. By assessing the core area of erosion and slope failure hazard, advance action could be taken to improve preventing technique as well as minimizing severe damage.

3.4. Conclusion

High resolution remote sensing data such as LiDAR provides valuable information for hazard mapping. Full integration with powerful GIS tools allowed effective terrain simulation and improve our understanding by the provision of three dimensional visualizations. The method presented in this paper optimized the utilization of high resolution LiDAR data in simulating secondary terrain parameters for slope failure hazard assessment. For terrain analysis, all factors were computed by considering two main attributes which are slope steepness and hydrological effects. The result of this study suggest that LiDAR data at 1m resolution are valuable to provide preliminary insight into several terrain processes related to erosion development and slope failure hazard assessment. The simulated map reveals critical areas of concern but further validation using field measurement is still necessary. Accuracy value could be improved by additional data on environmental and ecological aspects. The analytical method and result discussed in this paper suggest that terrain-based erosion model would become an effective tool for predicting and estimating slope failure hazard associated with forest road construction in the areas. Information obtained will be beneficial to highlight areas that are potentially vulnerable to severe erosion and/or slope failure with respect to the terrain shape and characteristics. An effective forest management will reduce inventory time, high cost and labour works especially in complex and steep forested area.

Chapter III is adapted and restructured from Azita Ahmad Zawawi, Masami Shiba, Noor Janatun Naim Jemali. 2014. Simulation of terrain attributes from LiDAR data for slope failure hazard assessment in steep forest of Okinawa Island. *Journal of The Japan Forest Engineering Society* 29(4):193~202

Chapter IV

Terrain Condition on the Distribution of Stand Structure and Diversity in Subtropical Yambaru Forest, Okinawa

4.1 Introduction

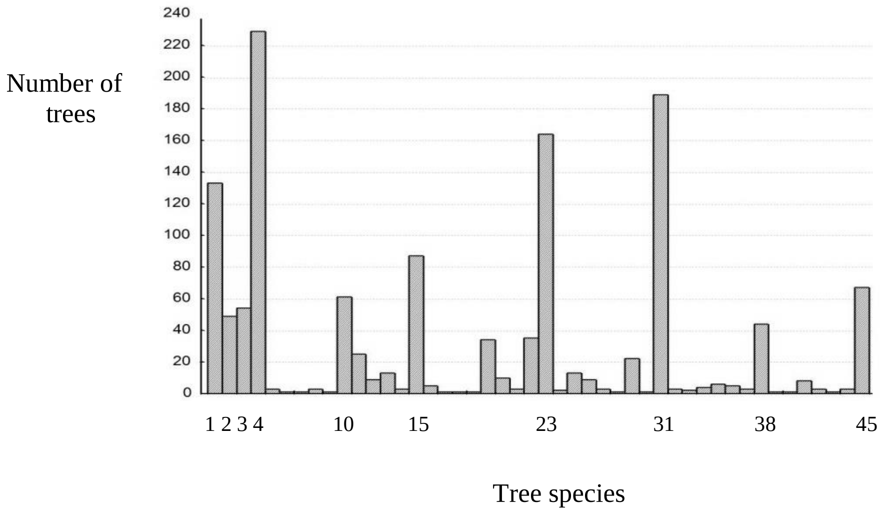
Altitude and topography are important factors that affect precipitation, temperature, solar radiation and vegetation composition. Abarghoie et al. (2011) revealed that elevation had a significant influence on richness, diversity, and uniformity and that species richness and species diversity were highest on high slopes of 30-50% inclination. One of the most important effective factors on the variation species diversity is geographical direction (Zareh-Chahoky et al. 2009). Terrain factor affects the distribution and abundance of soil moisture and precipitation which influence the distribution, composition and abundance of vegetation (Yeakley et al. 1998). Many studies discussed that topographic variation, especially elevation, slope position and aspect influenced vegetation and soil condition (Jarvis & Mulligan 2009, Reza et al. 2013), as well as site index, forest productivity and species composition (Trimble & Weitzman 1956, McNab 1993, Villwock et al. 2011). The recognition of terrain characteristics through digital mapping will help in the prediction of vegetation composition based on species-terrain relationship (Narayanaraj et al. 2010). In Okinawa, several studies relating to this subject has significantly contributed to the forest research and development. Yamamori and Oyama (1973) are among the pioneers who studied forest stand composition on different topography. The studies continue for decades and among popular reviews are studies by Enoki (2003) who examined the micro topography and distribution of canopy trees in Yambaru, and another study by Kubota (2004) who assessed the influenced of topographic heterogeneity on tree species richness and dynamics. Most studies, however, focused on only several terrain parameters such as slope position and aspect, but less coverage on other factors.

Generally, vegetation distribution differs depending on the spatial pattern of soil type and climatic variables. In the case of tropical and most subtropical forests, previous studies suggested that stand structure, vegetation distribution, and species composition are generally influenced by two main factors which are; i) the temporal dynamic of disturbance and succession (Grubb et al. 1975, Ohsawa & Ozaki 1992, Chen et al. 1997) and ii) environmental variability such as topographic exposure and geomorphological aspect (Enoki 2003, Kubota et al. 2004). In this study, holding on to the similar theoretical concepts, several interesting terrain parameters were introduced and discussed.

This study was done to evaluate the relationship of terrain influences on stand structure and species diversity in Yambaru subtropical forest of Okinawa Island. Variables studied were elevation, geographical aspect, slope, TW index, and TR index. The result of this study can be utilized to predict existing plant communities by the determination of its topographical elements. Assessment of site characteristics and its relationship to forest structure provide essential information and encourage critical discussion for sustainable forest management planning.

4.1.1 Forest characterization

Forest area in the island is characterized by short-bold trees and larger trees having spreading crowns, forming a close canopy of rounded crowns (Shinohara et al. 1996). **Figure 4-1** shows the distribution of tree species recorded in the study site. The forests are rich in species where 45 species were found within the study site (**Appendix-8**). Based on our field inventory, the mean number of species per plot was 20. The graph highlights the dominant species which are *Castanopsis sieboldii* and *Daphniphyllum* *glaucescens*. **Figure 4-2** shows the distribution of experimental plots within the selected forest site.



Code	Species
1	*Syzigium buxifolium*
2	*Distylium racemosum*
3	*Schima wallichii*
4	*Castanopsis sieboldii*
10	*Rhaphiolepis indica*
15	*Elaeocarpus japonica*
23	*Myrsine segunii*
31	*Daphniphyllum glaucescens*
38	*Ternstroemia japonica*
45	*Ilex liukiuensis*

Figure 4-1. Distribution of tree species recorded in the study site. As labeled are the dominant species based on stem density

4.2 Materials and methods

4.2.1 Study area

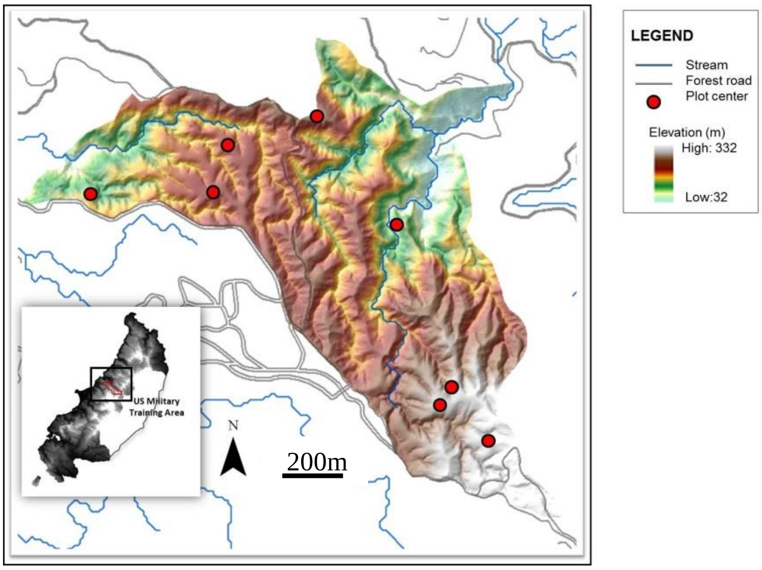


Figure 4-2. Selected experimental plots established in the study site

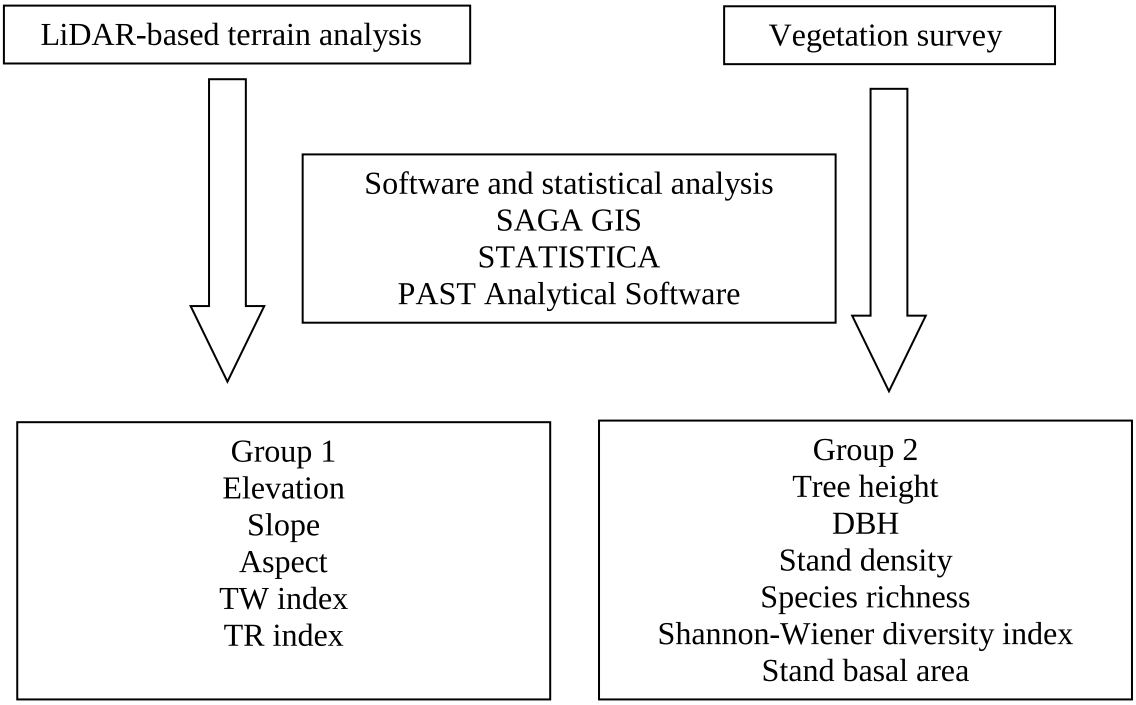


Figure 4-3. Research framework of the assessment

Figure 4-3 shows the steps of analyses and research flow. Analysis was divided into two phases: LiDAR-based terrain analysis and vegetation survey. In this study, eight experimental plots of 20 x 20m were randomly selected as representative of the forest area. The criteria for plots selection were their scattered location, topographical heterogeneity, and accessibility. Each selected plot represents the existing range of stand density, high canopy closure, and mixed-species in the forested watershed. Small number of plots were selected correspond to the limited accessibility for ground truth survey due to topographical characteristics, weather condition, and labor constrain.

4.2.2 LiDAR-based terrain analysis

Terrain variables were derived from the DTM of the study area which was generated from the LiDAR data at 1m resolution, by assigning the last return value of the laser pulses. Laser scanner data were recorded on April 2011 using ALTM 3100

(CASI-3). The laser wavelength was 1064nm with scan frequency and scan angle of 39Hz and ±20°, respectively. The flight altitude was 1100m with footprint size of 0.2mrad. The LiDAR system was operated to record two returns per pulse, which were the first return and the last return. SAGA GIS software and ArcGIS 9.3 was efficiently used for data processing and statistical analysis. Elevation, slope, aspect, TR index, and TW index were generated from the DTM extracted from the eight experimental plots. The numerical formula was done following SAGA GIS module (**Appendix-9**).

4.2.3 Vegetation survey

All trees with diameter at breast height (DBH) larger than 3.0cm were recorded and tree species were indentified. Tree height was measured for selected trees using a 12m pole with scale.

4.2.4 Statistical analysis

For each site, vegetation diversity indices were correlated to the mean values of independent terrain variables derived from the DTM with probability value of $p = 0.05$ to determine the significance of each relationship. The statistical analyses were done using STATISTICA analytical software.

4.3 Results and discussions

4.3.1 Height estimation based on plot level assessment

Mean canopy height for the eight selected plots was 6.9±2.5m, with a minimum of 3.3m and maximum of 20.3m (**Table 4-1**). **Figure 4-4** illustrates the relationship between DBH and tree height with r value of 0.83.

Table 4-1. Descriptive statistic of DBH and tree height

Variable	Mean	Min.	Max.	SD
DBH (cm)	9.75	4.00	47.70	7.08
Height (m)	6.95	3.33	20.30	2.53

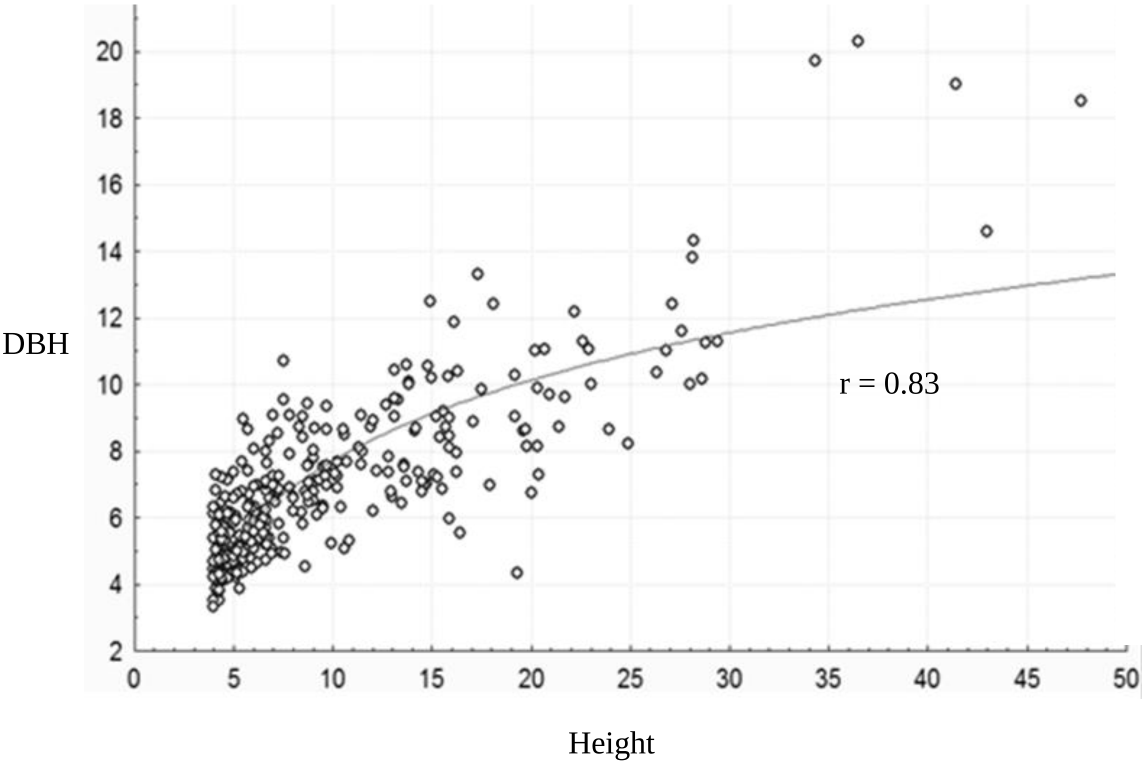


Figure 4-4. Scatter plot of tree height and DBH explains the relationship between the two variables

Table 4-2. Descriptive statistics of DBH range, height range, stand basal area, tree density and number of species in each plot

Plot/ Variable	DBH (cm)	Height (m)	Stand basal area (m^2ha^{-1})	Density (stems ha^{-1})	Species' richness	Shannon -Wiener
1	7.6±5.4	5.7±1.4	21.5	179	15	2.3
2	8.8±5.0	6.1±1.3	33.2	205	15	2.3
3	15.7±13.4	10.8±4.2	49.4	73	24	2.7
4	9.6±5.6	6.8±1.5	33.3	196	22	2.4
5	9.3±5.7	7.9±2.1	34.4	161	30	2.9
6	10.5±6.7	6.9±2.4	30.0	127	26	2.5
7	7.7±3.9	5.4±1.0	18.3	184	18	2.4
8	9.9±6.9	6.8±1.9	34.5	209	23	2.6

Table 4-3. Mean value and standard deviations of terrain variables at plot level

Plot	Elevation (m)	Slope (°)	Aspect (°)	TW index	TR index (m)	Landform type
1	202±0.6	6.7±4.4	86.5±83.7	3.9±1.2	0.1±0.05	Open slope
2	217.8±0.6	8±3.5	131.5±105.6	3.8±1.1	0.1±0.04	Midslope
3	148.7±0.6	31.5±4.6	253.7±54.9	2.5±0.8	0.4±0.1	Valley
4	249.3±0.6	6.9±4.0	198.9±54.9	3.8±0.8	0.09±0.05	Upper slope
5	263.1±2.4	22.9±4.9	332±21.6	3±0.8	0.3±0.07	Upper slope
6	172.4±2.1	20.9±4.8	81±72.7	3.1±0.7	0.3±0.07	Midslope
7	205±0.2	4.4±3.2	223.4±72.7	3.9±1.2	0.06±0.04	Plain
8	249±1.9	17.3±7.5	242.6±41.8	3.5±0.6	0.2±0.1	Upper slope

The entire selected subsets represent high canopy closure and multi storey forest stand. Plot 3 recorded the lowest value of tree density but higher value of tree height, DBH, and stand basal area ($49.4m^2ha^{-1}$). The highest number of species was recorded in Plot 5 (30 species), while the lowest number of species was recorded in Plot 1 and Plot 2, both with only 15 species. Plot 7 recorded the lowest value of stand basal area with $18.3m^2ha^{-1}$. The result recorded that the mean tree height and DBH did not differ significantly among the 8 plots, but the maximum tree height was observed to be different. Tree height and DBH were higher in valleys than on ridges (**Table 4-2**, **Table 4-3**).

4.3.2 Relationship between terrain characteristics and vegetation structure

Table 4-4 shows results of correlation analysis conducted to all variables, and **Table 4-5** highlights the significant correlations. Correlation analysis conducted between terrain variables and vegetation indices presented interesting results. Stand density was positively correlated to elevation and negatively to slope position. Species richness shows a strong correlation to aspect, while Shannon-Wiener diversity index was positively correlated to slope position, aspect, and TR index, and negatively to TW index. Tree height and DBH both correspond to slope position, TW index and TR index.

Our observation showed that higher tree densities were found in plots established on ridges compared to valley and lower elevation. Tree height and diameter are good indicators to examine the vegetation resistance to wind. Many studies showed that tree height is generally greater on lower slope, where water saturation is greater and soil has a higher ability to supply nutrients. Elevation, slope and aspect are widely considered as useful predictors for environmental variables such as precipitation and solar radiation; which highly influence stand composition and structure. Slope position and direction influence surface moisture and correlated to aspect factor or direction of solar radiation which affect almost all tree indices being examined.

Table 4-4. Correlation values between variables

Variables	Vegetation indices	r	p-value
Elevation	Density	0.30	0.03
	Richness	0.46	0.26
	Shannon - Wiener	0.14	0.74
	Tree height	-0.06	0.89
	DBH	-0.26	0.53
	Stand basal area	-0.20	0.62
Slope	Density	-0.79	0.01
	Richness	0.55	0.16
	Shannon - Wiener	0.79	0.02
	Tree height	0.96	0.00
	DBH	0.79	0.02
	Stand basal area	0.79	0.01
Aspect	Density	-0.14	0.74
	Richness	0.87	0.00
	Shannon - Wiener	0.71	0.04
	Tree height	0.46	0.26
	DBH	0.24	0.57
	Stand basal area	0.41	0.31
TW index	Density	0.57	0.14
	Richness	-0.63	0.09
	Shannon - Wiener	-0.84	0.01
	Tree height	0.98	0.00
	DBH	0.83	0.01
	Stand basal area	0.74	0.03
TR index	Density	-0.66	0.07
	Richness	0.41	0.31
	Shannon - Wiener	0.72	0.04
	Tree height	0.88	0.00
	DBH	0.71	0.05
	Stand basal area	0.74	0.03

Table 4-5. Terrain variables which correlated significantly to vegetation indices

Vegetation indices	Terrain variables
Density	Elevation, slope
Species' richness	Aspect
Shannon - Wiener	Slope, aspect, TW index, TR index
Tree height	Slope, TW index, TR index
DBH	Slope, TW index, TR index
Stand basal area	Slope, TW index, TR index

It was observed that tree height was lower at upper slope and open slope than at midslope and valley. This situation might have resulted from the stress effect of salty and windy conditions influenced by the constant arrival of typhoons from the ocean. Sakihama et al. (2008) revealed that forest ecosystem in YFA was largely influenced by sea salt throughout the year, which also affected canopy height especially on open slopes and ridges. Enoki et al. (2014) also suggested that taller trees could not tolerate windy effects and the dry and windy condition decreased tree height. In contrast, the opposite slope might have different conditions and should be producing taller trees as well as higher productivity.

In YFA, the spatial pattern and distribution of vegetation also varied as influenced by forests stand history as well as the effects of disturbance (Fujii et al. 2010 & 2009, Kubota 2005). In addition, it was studied that some species have specific characteristics and adaptability regarding the site location and resilience towards typhoon and windy effects (Enoki et al. 2014, Santos et al. 2008). In this study, however, we do not evaluate the spatial distribution pattern of each tree by species as our main objective was to assess the relationship of stand structure with terrain characteristics.

4.3.3 Limitations and research constraints

In this study, due to a small number of sample plots, our results might suggest a low precision. Nevertheless, the results presented here showed a similar tendency to that of the previous studies. To improve the accuracy and assessment, extended analysis with more samples should be done. In addition, cluster analysis shall be conducted to group the vegetation type/species, based on topographical characteristics or their niche.

4.4 Conclusion

Landform and terrain characteristics influence the distribution of humidity associated with thermal and hydrological processes in various ways. This factor directly affects forest structure and vegetation pattern. This study highlights interesting discussion on the relationship between variables in the forest stand, which are very beneficial to enhance forest management planning and conservation strategy in Yambaru.

Chapter V

General Conclusion

5.1 Overall structure of the research

This study introduced alternative methods to map terrain variability for forest site evaluation and management planning. Assessments were conducted in selected forest sites within the YFA in the northernmost part of Okinawa Main Island, Japan. In this study, terrain characteristics of the YFA were analyzed to examine the various aspects of topography and their influence on environmental issues. The factors studied were crucial for erosion hazard assessment, risk management, site suitability as well as forest management and monitoring. The study highlighted several significant terrain factors and suggested the importance of secondary terrain attributes. Assessments were done according to site-specific characteristics such as topography, forest type, managements and land use planning. Terrain analysis and assessments were conducted using various factors including hydrologic and drainage network, slope, tree height, forest road, as well as land use. Spatial analyses were conducted using various geospatial tools within GIS. Map interpretation was made based on an extensive review and discussion with experts. The study objectives were divided into three main sections, which are:

Section 1: The quantification of landform characteristics for site evaluation and forest management planning in YFA, with the integration of a traditional concept.

Section 2: The simulation of terrain factors to identify slope failure hazardous sites in the steep forest of YFA.

Section 3: An assessment of the relationship between terrain characteristics and forest stand structures in YFA.

Terrain characteristics were computed using DTM within GIS. Spatial relationships discovered in this study were presented in the form of digital maps, and interpretation was conducted based on visual examination as well as extensive review of literature. Maps produced reflected landform types, slope level, and other terrain categories, which correlated to environmental factors, forest structure, and site suitability. The visual interpretations of maps vary depending on the research objective. For each chapter in this thesis, information obtained was critically discussed to address potentially vulnerable forest sites with respect to their terrain shape and characteristics.

5.2 Yambaru: What matters most?

The mountains of Yambaru are located near the coast and the coastal facing slopes receive a higher amount of precipitation while the opposite slopes receive shadow rain and slower winds resulting in a drier climate. In Okinawa, despite soil quality, terrain attributes are the primary factor for contributing to successful forest growth. Species compositions of trees have been observed to vary between sites, landform types, and slope positions. As mentioned earlier in this study, it was discussed that flat terrain and gentle slopes were considered to be at the lowest grade for forest growth, where wind exposure is high and allows for full maximum effects from typhoons. This situation was explained by lower NDVI values and low tree heights, which were recorded on open slopes and high ridges. Areas that receive higher exposures to solar and wind are very sensitive, suggesting restrictions for forestry related activities. Improper forest site development will contribute to slope failure and this will indirectly affect the coastal zone, damaging lower vegetation and influencing aesthetic values. Nevertheless, we have discussed in the first section where this issue could be controlled by planting wind resistance trees along sensitive sites.

Terrain analysis and classification based on DTM is very cost effective and time saving, as it provides basic, but important information for rational land use especially on Okinawa Island for dealing effectively with severe environmental and economic constraints. The presented results and discussions in this study provided an interesting outlook of historical concepts and their re-interpretation using a modern approach. Through a deeper understanding of the terrain characteristics, potential and specific constraints of the forest could be detected. Information and analytical methods discussed in this study will be valuable for forest management planning, especially in the complex subtropical forest of Okinawa Island.

5.3 Limitations of the study and future recommendations

The integration of a digital terrain analysis with GIS provides powerful tools and an interesting approach for extracting topographic features derived from digital remote sensing data and satellite images. Each chapter in this thesis discusses the potential use of DTM for terrain classification and site evaluation where the analysis and interpretation was conducted from the perspective of a slope position factor. We agree that DTM alone is not sufficient enough for site evaluation, and more environmental data are needed as indicators. It is also agreeable that rainfall and climatic factors play an important role in the indices calculation. Adequate data on rainfall intensity and water flow will produce more accurate results. In this study, supported by literature reviews, all simulations assumed that the study area received a uniform amount of rainfall and consists of a homogenous soil type. In accordance with our main objectives, the relationships of all terrain factors with slope position and hydrological effects were analysed.

The results of this study suggested that DTM data both at 10 and 1m resolutions were valuable for providing preliminary information of terrain processes and their influences on forestry related activities. Maps produced from the analyses revealed the critical areas of concern, but further validation using detailed field measurements are very important for their long-term assessment. In previous chapters, we have discussed that accuracy values could be improved by adding more data on environmental and ecological aspects and how supporting data from satellite images or remote sensing could improve these evaluations through a predictive terrain modelling within geospatial applications. With regards to dynamic terrain characteristics, more case studies and a repetitive analysis at the local level are needed to allow further assessment of YFA.

In conclusion, the lack of data on forest structure and terrain characteristics of YFA could be overcome with the integration of GIS and high resolution spatial data. A detailed forest evaluation should be possible even though ground assessment is still limited due to restricted accessibility, high requirement of labour or time constrains. Technological improvements and advances of alternatives for forest assessments will allow continuous forest monitoring when it comes to achieving successful forest management planning.

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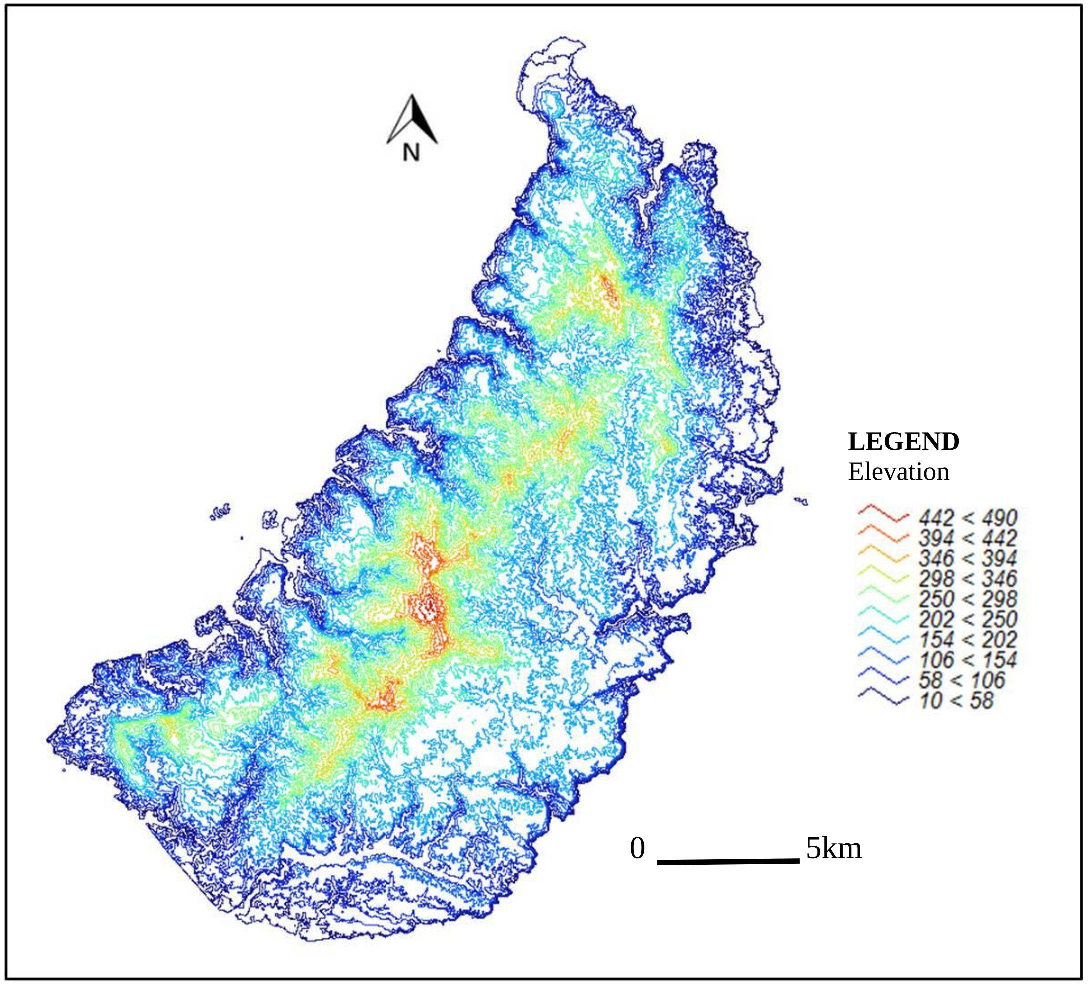
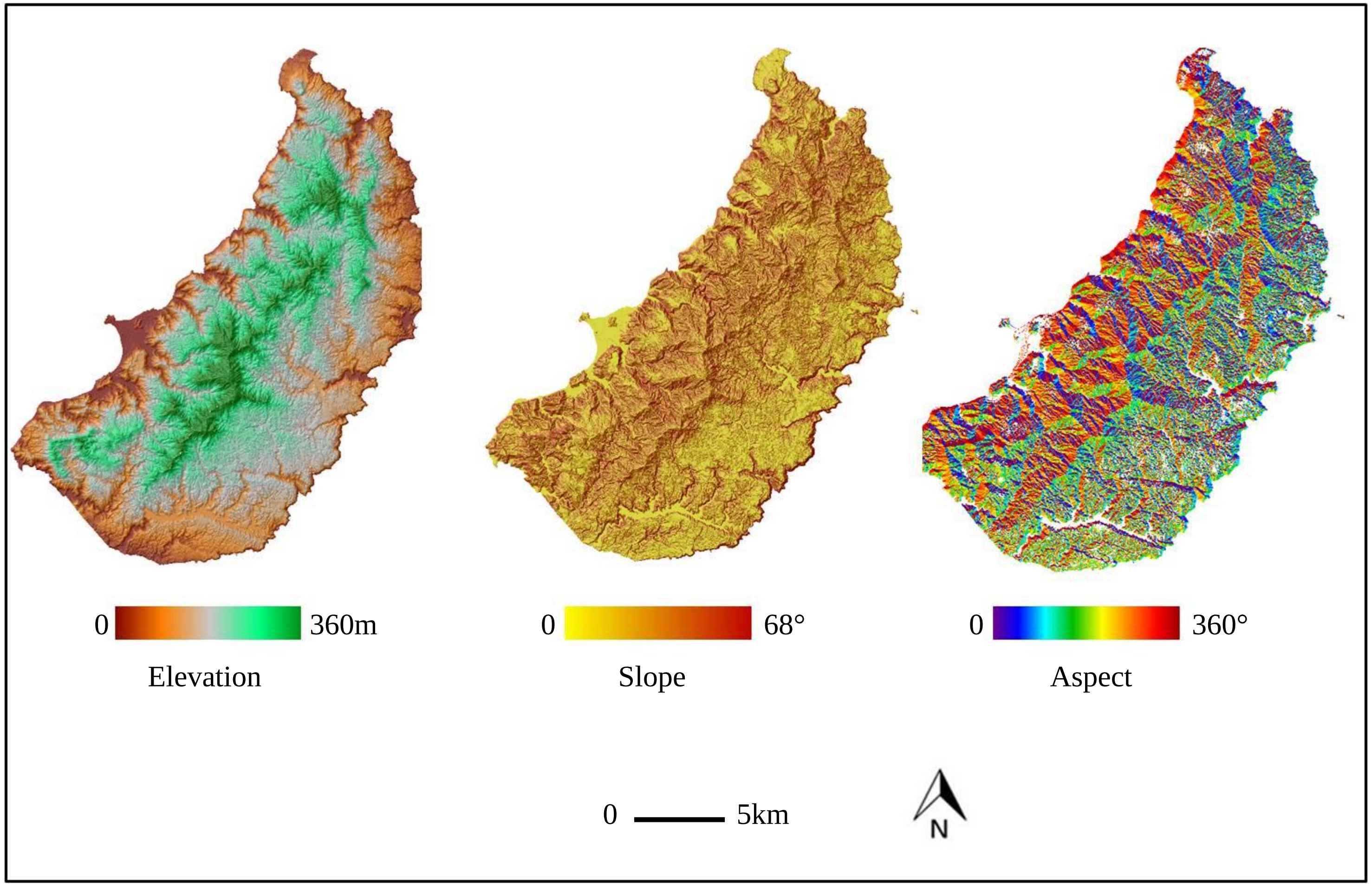
Apppendices

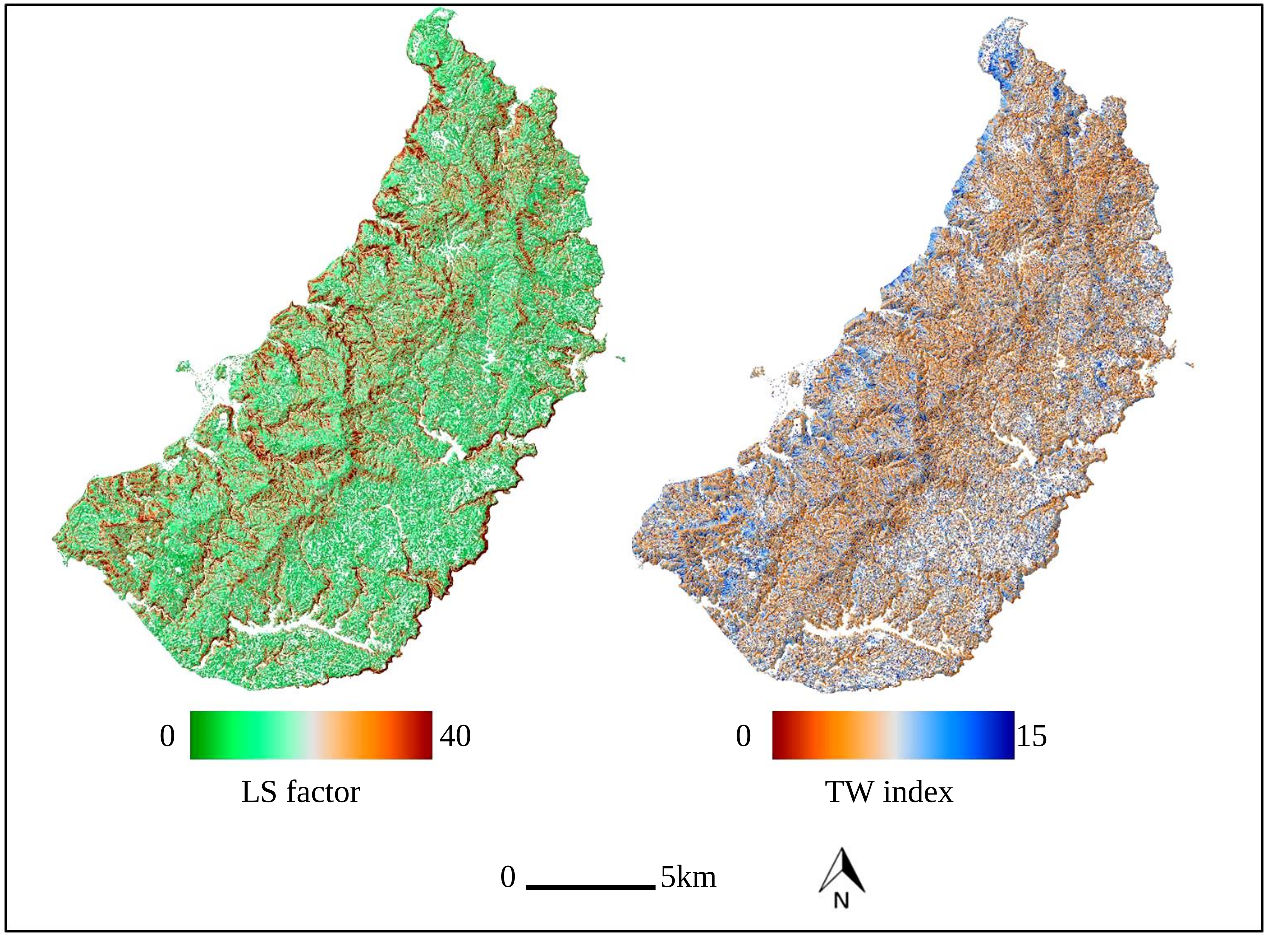
Appendix-1. Contour map of Yambaru (Contour distance 30m)



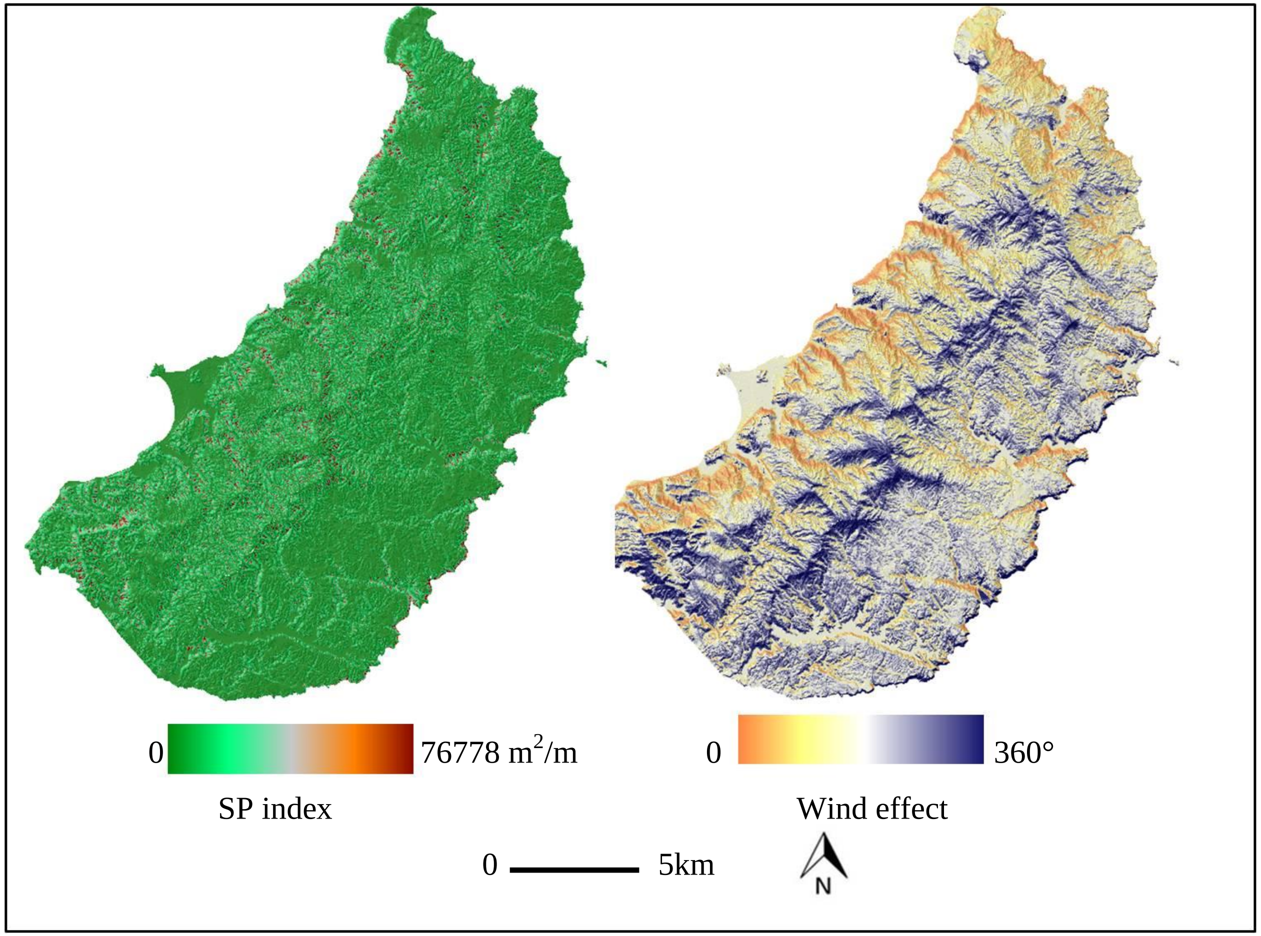
Appendix-2. Maps of elevation, slope and aspect of Yambaru



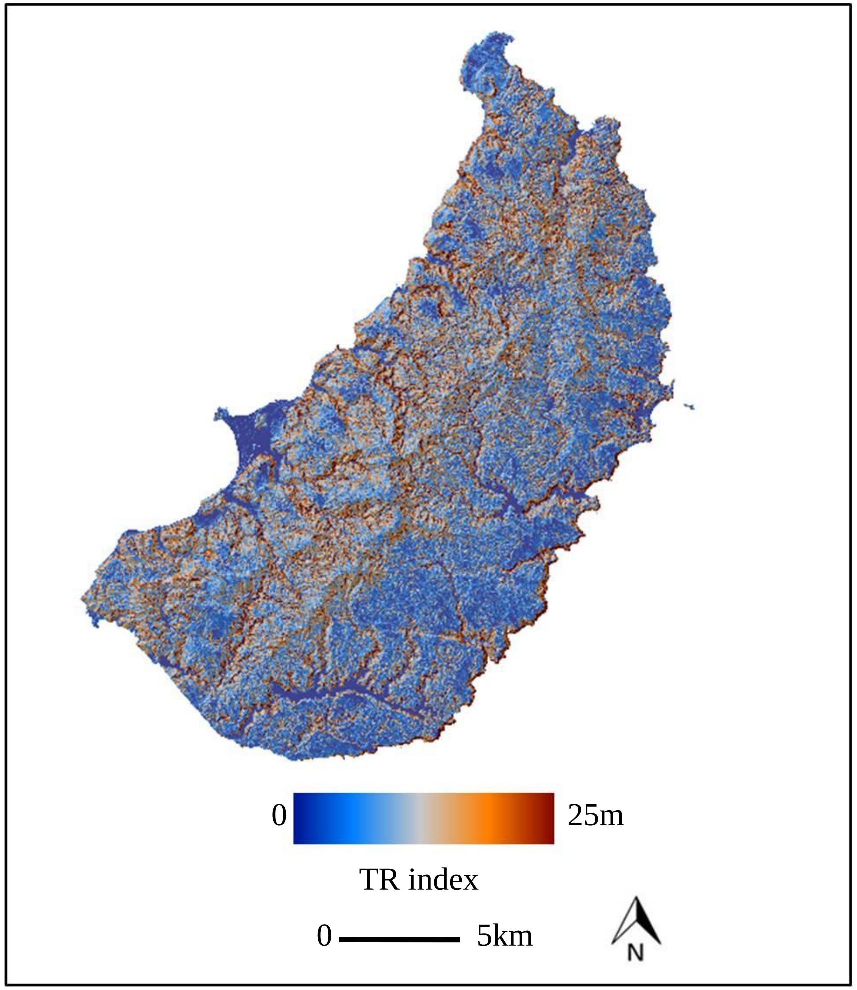
Appendix-3. Maps of LS factor and TW index of Yambaru



Appendix-4. Maps of SP index and Wind effect of Yambaru



Appendix-5. Map of TR index of Yambaru



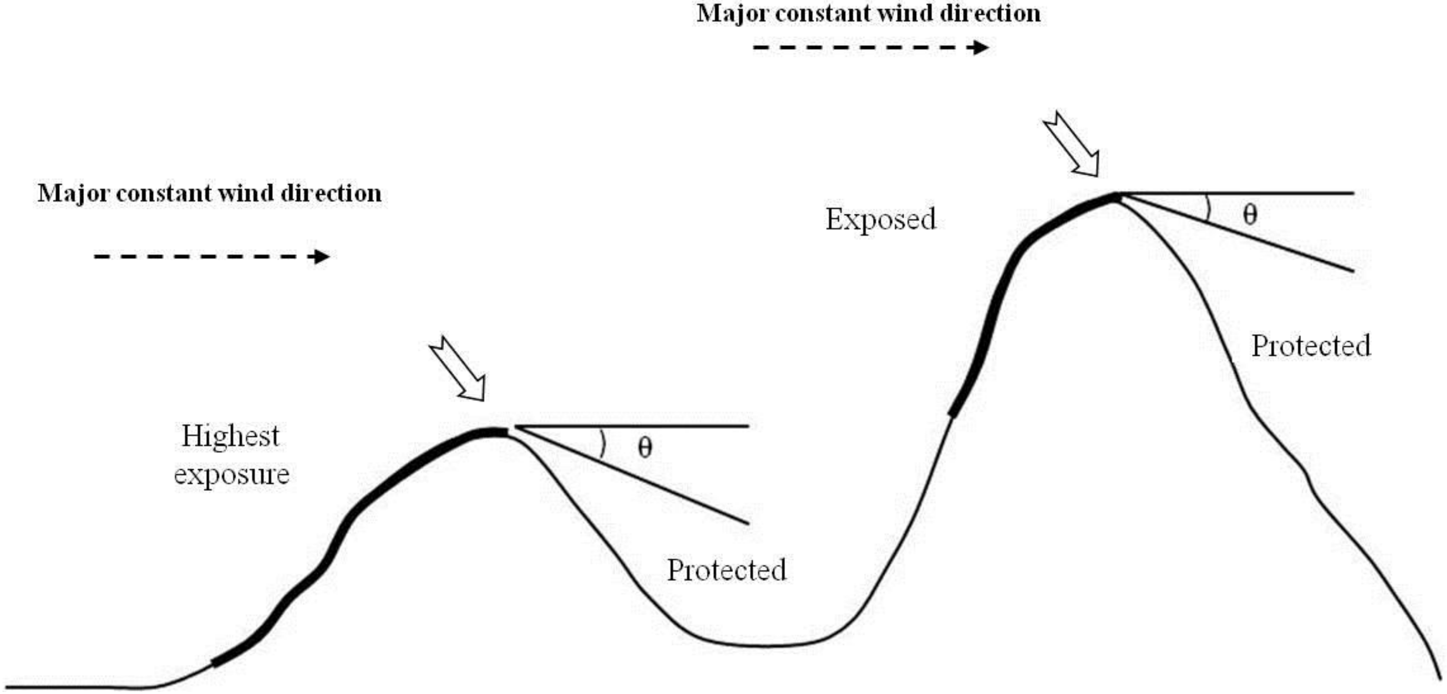
Appendix-6.

Descriptive statistics of terrain variables in Yambaru

Terrain variable	Minimum	Maximum	Mean±SD
Elevation (m)	0	503	160.5±85.1
Slope (°)	0	42.5	18.1±12.2
Aspect (°)	0.5	360	188.9±104.7
LS factor	0	35.7	5.1±3.5
TW index	0.7	15.2	4.6±1.5
SP index (m^2/m)	0	76778.8	308.8±797.8
Wind effect (°)	40	360	51.6±5.7
TR index (m)	0	25	2.6±1.8

Appendix-7

The concept of topographical exposure adapted from Sai On (1768), Boose et al. (1994) and Mikita & Klimanek (2010)



Appendix-8.

List of tree species recorded within the sample plots

Sp code	Scientific name	Local name
1	*Syzigium buxifolium*	Adeku
2	*Schima wallichii Liukiuensis*	Iju
3	*Distylium racemosum*	Isunoki
4	*Castanopsis sieboldii*	Itajii
5	*Neolitsea aciculata*	Inugashi
6	*Podocarpus macrophyllus*	Inumaki
7	*Styrax japonica*	Egonoki
8	*Ilex warburgii*	Oshiibamochi
9	*Glochidion acuminatum*	Okinawa ushirogashi
10	*Rhaphiolepis indica var. insularis*	Okinawa Syarimbai
11	*Dendropanax trifidus*	Kakuremino
12	*Vaccinium wrightii*	Gima
13	*Symplocos lucida*	Kuroki
14	*Symplocos prunifolia*	Kurobai
15	*Elaeocarpus japonicas*	Kobanmochi
16	*Cleyera japonica*	Sekaki
17	*Rhododendron tashiroi*	Sakura azalea
18	*Camelia sazanqua*	Sazanka
19	*Cinnamomum doederleinii*	Shibanicckei
20	*Randia canthioides*	Shimamisaonoki
21	*Neolitsea sericea*	Shirodamo
22	*Tricalysia dubia*	Shiromimizu
23	*Myrsine segunii*	Taimin Tachibana
24	*Persea thunbergii*	Tabunoki
25	*Ilex goshinensis*	Tsugemochi
26	*Diospyros morrisiana*	Tokiwagaki
27	*Meliosma lepidota*	Nambanawabuki
28	*Rhus succedanea*	Hazenoki
29	*Eurya japonica*	Hisakaki
30	*Tutcheria virgata*	Hizekaki sazanka
31	*Daphniphyllum glaucescens ssp. teijsmannii*	Himeyuzuriha
32	*Schefflera octophylla*	Fukanoki
33	*Schoepfia Jasminodora*	Boroboronoki
34	*Symplacos confusa*	Miyamashirobai
35	*Ilex maximowicziana*	Mutchagara
36	*Microtropis japonica*	Mokureishi
37	*Ilex integra*	Mochinoki
38	*Ternstroemia japonica*	Mokkoku
39	*Osmanthus okinawensis*	Yanagibamokusei
40	*Camellia japonica*	Yagujibaki
41	*Myrica rubra*	Yamamomo
42	*Symplocos okinawensis*	Ryukyuhainoki
43	*Pinus Luchuensis Mayr*	Ryukyu matsu
44	*Osmanthus marginatus*	Ryukyumokuzai
45	*Ilex liukiuensis*	Ryukyu mochi

Appendix-9.

Descriptive summary of terrain characteristics computed from the DTM data

Variables	Description
Elevation	Altitude above sea level, elevated terrain measured in meter.
Aspect	The slope azimuth, or the compass direction that a slope faces, have strong influences on temperature and wind exposure. Measured in degree (°)
Slope	Gradient of the terrain. Measured in degree (°)
LS factor	The measurement between length of slope and steepness of the slope. Represent the effect of slope length and slope steepness on erosion. LS factor = $(A / 22.13)^t (\sin \beta / 0. 0896)^1$
TW index	Topographic wetness index: Prediction of saturation level, assumption that the area has uniform soil properties). TW index = In $(A_s / \tan \beta)$
SP index	Stream power index: Prediction of erosive power of flowing water, assumption that discharge is equal to specific catchment area. Measurement unit : m^2/m SP index = $A_s \tan \beta$
TR index	Terrain ruggedness index: The effects of slope and terrain undulations6), sometime used to measure surface texture and smoothness. TR index = (TNC x TNF) / (TNC + TNF)
Wind effect	Applied to measure wind exposure index, and/or wind shelter index The combination of wind speed and wind direction.

Appendix-10

Publications

1. **Azita Ahmad Zawawi,** Masami Shiba, Noor Janatun Naim Jemali. 2015. Accuracy of LiDAR-based tree height estimation and crown recognition in a subtropical evergreen broad-leaved forest in Okinawa, Japan. *Forest Systems* (In Press).

2. **Azita Ahmad Zawawi,** Masami Shiba, Noor Janatun Naim Jemali. 2014. Simulation of terrain attributes from LiDAR data for slope failure hazard assessment in steep forest of Okinawa Island. *Japanese Journal of The Japan Forest Engineering Society* 29(4):193-202.

3. **Azita Ahmad Zawawi,** Masami Shiba, Noor Janatun Naim Jemali. 2014. Landform classification for site evaluation and forest planning: Integration between scientific approach and traditional concept. *Sains Malaysiana* 43(3): 349-358.

4. **Azita Ahmad Zawawi,** Masami Shiba, Hazandy Abdul Hamid, Mohd Zaki Hamzah, Pakhriazad Hassan Zaki. 2012. Preliminary assessment on the differentiation in wood structure and properties of *Beackea frutescens* as impacted by recreational activities in Mount Tahan, Malaysia. *Sains Malaysiana* 41(9): 1085-1089.

5. Noor Janatun Naim Jemali, Masami Shiba, **Azita Ahmad Zawawi.** 2013. Comparison of image classification methods using IKONOS image for identifying land cover attributes of logged over forest area in Yambaru, Okinawa Island. *Japanese Journal of The Japan Forest Engineering Society* 28(1): 99-105.

Oral Presentations

1. **Azita Ahmad Zawawi,** Masami Shiba, Noor Janatun Naim Jemali. Topographic condition on the distribution of stand structure and diversity in subtropical Yambaru forest, Okinawa. Kyushu Branch of Forest Society (Annual Meeting). Saga University, 25th October 2014.

2. **Azita Ahmad Zawawi,** Masami Shiba, Noor Janatun Naim Jemali. Influence of topographic heterogeneity on tree diversity and structure in Yambaru forest. Annual Meeting on Okinawa Subtropical Forestry. 29th August 2014. (No printed abstract).

3. **Azita Ahmad Zawawi,** Masami Shiba, Noor Janatun Naim Jemali.Stand based tree height estimation and crown delineation using LiDAR in subtropical Yambaru forest, Okinawa. The Japanese Forest Society Congress 125. Omiya Convention Center. 26-30th March 2014. (Abstract C10-Page 76).

4. **Azita Ahmad Zawawi,** Masami Shiba, Noor Janatun Naim Jemali. Assessment of crown structure characteristics using LiDAR data in complex subtropical forest of Okinawa Island. Kyushu Branch of Forest Society (Annual Meeting). Miyazaki University. 26-28th October 2013.

5. **Azita Ahmad Zawawi,** Masami Shiba, Noor Janatun Naim Jemali. Estimation of complex crown patches using LiDAR data in Yambaru forest. Okinawa Island. Annual Meeting on Okinawa Subtropical Forestry. 30th August 2013. (No printed abstract).

6. **Azita Ahmad Zawawi,** Masami Shiba, Noor Janatun Naim Jemali. Simulating topographic potential for automated erosion detection: An evaluation of steep forest on Okinawa Island. IUFRO Unit 3.06 International Conference. Forest Operations in Mountainous Conditions. Honne, Norway. 2nd -5th June 2013. (Proceeding-Page 117-120).

7. **Azita Ahmad Zawawi,** Masami Shiba, Noor Janatun Naim Jemali. Terrain stability assessment on erosion hazard sites in Yambaru forests, Okinawa Island. The Japanese Forest Society Congress 124, Iwate University. 26 - 29th March 2013. (Abstract-Page 156).

8. **Azita Ahmad Zawawi,** Masami Shiba, Noor Janatun Naim Jemali. Simulating topographic effect for sensitive site assessment and risk mapping in subtropical forest of Okinawa Island, Japan. 2nd USM-PSU International Conference on Art and Sciences 2012, Penang, Malaysia. 2nd - 4th December 2012. (Abstract-Page 61).

9. **Azita Ahmad Zawawi,** Masami Shiba, Noor Janatun Naim Jemali. Digital Terrain Simulator (DTS) for detection of sensitive site and mapping in steep watershed forest of Yambaru Area, Okinawa Island. Kyushu Branch of Forest Society (Annual Meeting), Kumamoto University. 26 - 27th October 2012. (No printed abstract).

10. **Azita Ahmad Zawawi,** Masami Shiba, Noor Janatun Naim Jemali. Sensitive site detection and mapping in steep watershed forest of Yambaru based on Digital Terrain Simulator (DTS). Annual Meeting on Okinawa Subtropical Forestry. 31th August 2012. (Abstract-Page 21).

11. **Azita Ahmad Zawawi,** Masami Shiba, Noor Janatun Naim Jemali. Terrain analysis and site evaluation for sustainable management of subtropical forest in Yambaru, Okinawa. The Japanese Forest Society Congress 123, Utsunomiya University. 26 - 28th March 2012.(Abstract- D18).

Poster Presentations

1. **Azita Ahmad Zawawi,** Masami Shiba, Noor Janatun Naim Jemali. Estimating stand heights and crown structure of subtropical broadleaved forest using LiDAR data in Okinawa island, Japan. IUFRO World Congress. Salt Lake City, Utah. 5-11th October 2014. Poster No 164, Abstract No 1139.

2. **Azita Ahmad Zawawi,** Masami Shiba, Noor Janatun Naim Jemali. Landform Classification for Site Evaluation and Forest Planning: Integration between Scientific Approach and Traditional Concept. General Seminar of Agriculture I, Kagoshima Rendai, Kagoshima. 13th November 2013. Poster No 25.